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CONTENTS

PAGE

HEY, R. W. The Geomorphology and Tectonics of the Gebel Akhdar (Cyrenaica) 1
KIER, P. M. A New Genus of Echinoid from the Palaeozoic of Ireland 15
CHINNER, G. A., M. SANDO, and A. J. R. WHITE. On the Supposed Transformation of Tillite to Granite at Mount Fitton, South Australia 18
WELLS, A. J. Corundum from Ceylon 25
RAMSAY, J. G. The Supposed Moinian Basal Conglomerate at Glen Strathfarrar, Inverness-shire 32
HODSON, F. Carboniferous Goniatites from Ireland 41
HARRY, W. T. The Old Red Sandstone Lavas of the Western Sidlaw Hills, Perthshire 43
HARKER, R. I. The Stratigraphy and Folding of some Metamorphosed Moine Sediments around the Carn Chuinneag and Inchbae granitic gneisses 57
ATKINSON, D. J. The Occurrence of Chloritoid in the Hecla Hoek Formation of Prince Charles Foreland, Spitsbergen 63
BROWN, P. E. The Mourne Mountains Granites—A Further Study . 72

CORRESPONDENCE

Upper Eumorphoceras Beds on Benbrack, County Cavan 85

NOTICE—ZOOLOGICAL NOMENCLATURE
p. 85

REVIEWS
pp. 86–7

PUBLICATIONS RECEIVED
pp. 87–8

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The Geomorphology and Tectonics of the Gebel Akhdar (Cyrenaica)

By R. W. HEY

ABSTRACT

The main topographical features of the Gebel Akhdar are described, and attributed to various phases of marine and subaerial erosion. The tectonic structures of the Gebel are also described, and their relations to the erosional features are examined. On this basis an attempt is made to reconstruct the Late Tertiary history of the region in terms of earth-movements and erosional phases ; this is a period for which normal stratigraphical evidence is almost non-existent.

I. INTRODUCTION

THE Gebel Akhdar is a large and isolated area of high ground occupying much of northern Cyrenaica. It is roughly elliptical in plan, and about 250 km. long from east to west. The crest-line of the Gebel, rising in places to over 800 m., lies to the north, always within 50 km. of the coast. To the south of this line the ground falls very gradually towards the depressions containing the oases of Marada, Giarabub, and Siwa. To the east there is a similarly gentle fall. Northwards and westwards, however, the Gebel is limited by abrupt slopes in the form of two successive escarpments.

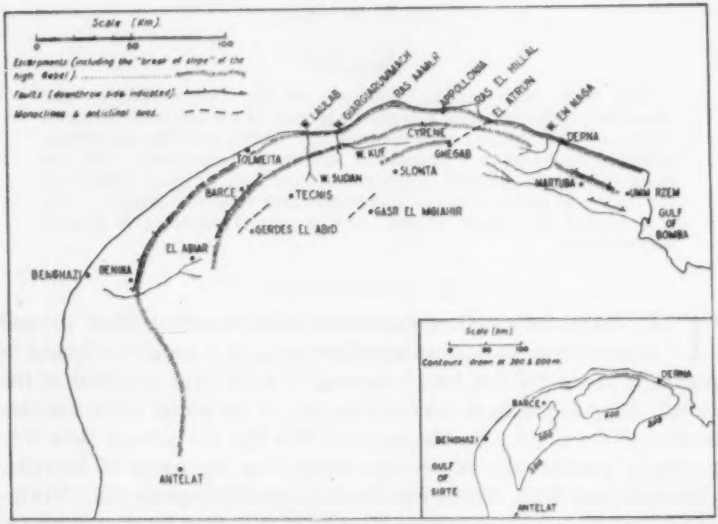
As can be seen from Text-fig. 1, these escarpments are of very great length. The higher of the two runs for about 300 km., the lower for over 400 km. ; both are almost unbroken except by the gorges of innumerable wadis.

Attempts to explain the Cyrenaican escarpments agree that neither can be ascribed to differential erosion, since both are cut in rocks of varying ages, dips, and physical properties. This, however, has left room for two alternative hypotheses : that the features are fault-scarps, and that they are largely due to marine erosion.

The earliest views on the subject seem to be those of Spratt, who believed that the plateaux of Libya were " variously elevated or depressed between lines of faults, well marked by their having deeply scarped faces along the lines of those faults . . ." (1865, p. 376). For

Cyrenaica itself this view was supported by J. W. Gregory, who claimed to have located five distinct faults within the territory, all but one being associated with an escarpment (1911, pp. 580–3 and 589–92, and pl. xlii).

Later, when the first detailed topographical surveys of the coastal regions were undertaken, it became clear that the escarpments were only two in number, though each of great length. It was then suggested by Marinelli (1920) that both might be wave-cut cliffs, formed during pauses in the original uplift of the Gebel. This idea was also upheld by Ahlmann (1928) and Stefanini (1930).



TEXT-FIG. 1.—Topography and known geological structures of northern Cyrenaica. Only the larger wadis are shown.

Meanwhile, knowledge of the geology of the Gebel had increased, and in 1934 Marchetti was able to confirm the existence of two of Gregory's faults. One was found to follow the lower escarpment to the north-east of Benina, eventually becoming a monocline traceable as far as Tolmeita. The other followed the upper escarpment and was traced from the Barce area for at least 30 km. to the south-west. In addition, Marchetti referred to two groups of faults running parallel to the coast between Derna and the Gulf of Bomba and between Cyrene and El Atrun (Marchetti, 1934, p. 324).

As a result of this confirmation, Desio then revived the idea that the escarpments might be directly ascribed to faulting or monoclinal warping. Marine erosion, in Desio's view, had been confined to

certain parts of the coastal plain, and had not played an important part (Desio, 1939, pp. 63–7).

The present writer (McBurney and Hey, 1955, pp. 19–71) ascribes the lower escarpment to marine erosion, carried out while the sea-level stood at a series of successively lower altitudes, from about 200 m. downwards. The process is thought to have begun in Calabrian (earliest Pleistocene) times. It was neither accompanied nor followed by any considerable earth-movements ; the changes of sea-level were eustatic, and the escarpment is not a fault-scarp. In so far as it coincides with known faults, it is regarded as a " fault-line scarp "; in other words, the faults are relatively ancient, and acted in some way as lines along which erosion was resisted.

In the present paper, an attempt is made to explain the upper escarpment and certain features of the Gebel which lie at still higher levels. It is based partly upon original observations, but to a large extent upon a study of the existing 1 : 100,000 maps and upon geological information published by Marchetti in 1938.

II. The Solid Geology of Northern Cyrenaica

It will be convenient at this point to give an account of the solid geology of the Gebel Akhdar and its surroundings.

1. *Stratigraphy*.—The stratigraphy of the region is reasonably well known, and seems to be both simple and uncontroversial. The latest general accounts are those of Desio (1935) and Marchetti (1938); the best available geological map is included in Desio's work, and is to a scale of about 1 : 3,000,000.

All the rocks exposed are sedimentary, and almost all are marine limestones. The oldest beds known are Upper Cretaceous ; these are confined to the two large inliers of Gerdes el Abid and Mgiahir on the crest of the Gebel, and a few localities on the north coast. Eocene and Oligocene rocks are more widespread, but these again are mainly confined to the Gebel itself. Most of the region, especially the part which lies outside the Gebel, is covered with Miocene rocks, those of the Middle Miocene (Helvetian-Tortonian) being particularly widespread. Younger rocks are of very limited distribution. The Pontian is unknown; the Pliocene is represented only by a few doubtful occurrences near the margins of the Gulf of Sirte, in which area also are certain deposits referred to the "Sahelian". The marine Pleistocene is almost wholly confined to the immediate vicinity of the coast.

Large non-sequences have been detected in certain localities, but angular unconformities seem to be uncommon.

2. *Structure*.—Throughout most of Cyrenaica the beds dip gently to the south. Tectonic complications are known from two areas only :

Marmarica (east of the Gebel), where some faulting has occurred, and the Gebel itself, where, as has already been seen, there are various considerable disturbances. The following discussion will deal with the latter area only, and will consist mainly of a review of material already published.

The most recent and most useful source of information is a study of the water-resources of Cyrenaica (Marchetti 1938) which contains an account of the changing levels of a bed of impervious marl near the base of the Oligocene. This bed is responsible for numerous very copious springs in the eastern half of the Gebel ; Gregory, who first noticed it at Cyrene, called it the " spring-forming marl " (Gregory, 1911, p. 585). By plotting the levels of the springs, Marchetti was able to draw contours for the horizon itself over a large part of the Gebel, between Wadi Kuf and a point about 12 km. east of Derna. In some areas these levels were supplemented by levels taken from another spring-forming horizon, 60–70 m. higher, in the Lower Miocene (Marchetti, 1938, pp. 135–144).

The resulting map (op. cit., fig. 29) shows clearly that most of the eastern Gebel consists of one broad and simple anticline. Its axis runs from south-west to north-east, striking the coast near El Atrun, a fact which accounts for an inlier of Cretaceous rocks in this vicinity. Inland the axis can be traced at least as far as Gheghab, a distance of 30 km. It has a decided plunge to the north-east.

All the contour-lines are perfectly continuous. This shows that no large-scale disturbance can exist along the line of the upper escarpment between Derna and Cyrene. Similarly, it disposes of certain other faults, suggested by Gregory and Ahlmann, which were supposed to run at right-angles to the coast.

Several other relevant pieces of information are contained in Marchetti's work. Further details are given of the faults between Derna and the Gulf of Bomba ; all are stated to run parallel to the escarpments, and one in particular appears to coincide with the upper escarpment from the neighbourhood of Wadi Derna as far eastwards as Umm Rzem (op. cit., p. 53 and p. 97, footnote). Some attention is paid to the area between Cyrene and El Atrun where a group of faults had already been reported by Marchetti in 1934 ; reasons are given for believing that they are confined to a limited area and that their total effect is small (op. cit., pp. 172–180). Finally, it is noted that the inliers of Gerdes el Abid and Mgiahir are both bounded on their north-west sides by monoclines throwing down to the north-west ; of these monoclines the former, at least, is faulted (op. cit., pp. 193–4 and fig. 38).

Marchetti has nothing to say about the existence of certain faults which, according to Gregory, follow the lower escarpment near Derna

and Apollonia, though one of his sections crosses the escarpment a little to the east of Derna and shows no dislocation (Marchetti, 1938, fig. 31). Further information on this point can, however, be supplied by the present writer, who has examined a large part of the coast between Derna and Tolmeita ; except between Apollonia and Ras el Hillal no signs of faulting could be found, and it was concluded that Gregory must have based his deductions upon fossils which were not in place.

The present state of knowledge can now be summarized in the following list, which comprises all those tectonic features of the Gebel whose existence appears to be certain. Their positions, and various other details, are shown in Text-fig. 1.

Faults and monoclines : (i) Benina-Tolmeita fault/monocline ; (ii) Barce fault ; (iii) Gerdes el Abid fault/monocline ; (iv) Mgiahir monocline ; (v) Martuba faults (between Derna and the Gulf of Bomba) ; (vi) Ras el Hillal group of minor faults.

Folds other than monoclines : (i) El Atrun-Ghegab anticline.

III. The Upper Escarpment

1. *Description.*—The upper escarpment is much the less impressive of the two. It is seldom precipitous and nowhere exceeds 150 m. in height. In many places, also, it has undergone heavy subaerial erosion.

At its south-western end, it first becomes perceptible near El Abiar. In this area subaerial erosion has been particularly intense. To the north-east, however, the escarpment soon becomes well defined, and runs without serious interruption as far as the country to the south-west of Derna. Here it is obliterated over a distance of more than 15 km. by a network of wadis. East of Wadi Derna the escarpment once more becomes prominent, and then finally peters out within less than 10 km. of the Gulf of Bomba. Some writers have suggested that it continues for some distance down the west side of the Gulf, but this, on the evidence of the existing maps, seems doubtful.

Between the two escarpments lies a strip of country with gentle slopes ; this will be referred to as the " upper terrace ". Its width is variable, with a maximum of over 25 km. in western Cyrenaica and a minimum of 3 km. behind El Atrun. Like the upper escarpment, it has suffered much from subaerial erosion. At the south-western end of the terrace " karst " erosion has predominated, and has advanced so far as to create a series of inland drainage basins ; these, with their thick deposits of terra rossa, form the fertile plains of Barce and El Abiar. Elsewhere the effects of erosion are mainly in the form of dissection by deep and numerous wadis.

These wadis, however, are seldom wide, and east of Derna they are not even numerous. Except towards the south-west, there are in fact large areas, both on the terrace and on the escarpment, which show no obvious signs of subaerial erosion. On the terrace itself these areas appear to form part of a single smooth rock-cut platform, with a gradient which is always towards the sea and usually less than 1 in 50. The escarpment also, between wadis, has a simple and regular slope, seldom interrupted by subsidiary terraces ; the few which exist, such as those below Cyrene noted by Marinelli (1920, p. 78), appear to the writer to be merely the effects of local differential weathering.

The foot of the escarpment is comparatively well defined, and its profile often shows a sharp angle (see Text-fig. 3). Its height above sea-level varies greatly from place to place. These variations will be described in detail below ; for the moment it need only be said that they take the form of broad undulations. It should also be added that similar and more or less parallel undulations are shown both by the crest of the escarpment and by the surface of the upper terrace as a whole.

2. *Origin.*—It will already be clear that the upper escarpment, like the lower, cannot be a fault-scarp ; although the parts near Barce and to the east of Derna are associated with faults, the part between Derna and Cyrene is not. Once again, therefore, some form of erosion must have been responsible, the faults having merely succeeded in holding up its progress locally.

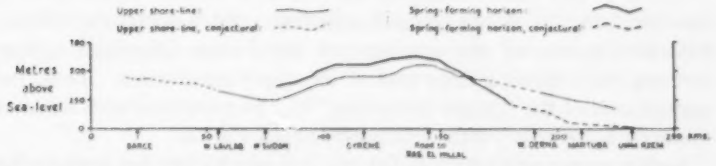
Differential erosion can be ruled out, for the upper terrace is composed of rocks of every age from Middle Eocene, in its central part, to Middle Miocene at either end. Nor is it likely that the upper terrace is a pediment, as described, for example, by Johnson (1932, and 1944, p. 796) ; its inner edge is too well defined and too regular in plan, and its surface bears no features corresponding to Johnson's " rock-cut fans ".

One possible hypothesis remains: that the terrace is a wave-cut platform, and the escarpment its associated cliff, formed, unlike the lower escarpment, during a single period of high sea-level. With this theory the simple profiles of terrace and escarpment are in perfect agreement, but there are two obvious objections: no post-Miocene marine deposits have yet been found on the terrace, and the foot of the escarpment is far from horizontal.

The first of these objections, however, is unimportant ; even on the undoubted marine terraces of the lower escarpment contemporary deposits are very scanty. Nor can the second objection be regarded as final, since there is no reason why marine erosion should not have been followed by tectonic warping. It is believed, in fact, that the evidence of the profiles is strong enough to show almost conclusively that marine

erosion did occur,[1] and that it was indeed followed by considerable earth-movements.

On the assumption that this hypothesis is correct, a diagram has been constructed (Text-fig. 2) to show the present levels of the shoreline to which the terrace and escarpment would have corresponded, and thus to show the nature of its subsequent distortion.[2] From the Gulf of Bomba as far as Wadi Laulab it has been assumed that the shoreline would have lain at or near the foot of the escarpment, the levels of which are taken directly from the 1 : 100,000 maps. To the south-west of W. Laulab the first signs of large-scale karst erosion appear, and from here onwards it is evident that this alone governs the levels of the foot of the escarpment. For some distance further, nevertheless, sufficient relics of the old terrace surface remain to give some idea of the levels at which the foot of the escarpment originally stood. To the south-west of Barce, however, the plain becomes so wide and so heavily eroded that attempts to continue the line must finally be abandoned.



TEXT-FIG 2.—Levels of the "upper shoreline" and of the "spring-forming marl".

It can be seen from the figure that the shore-line has been thrown into a series of undulations which are smooth and gentle but of very large amplitude. At its eastern end, where it can first be traced, it lies only 150 m. above sea-level ; this is its lowest point. From here it rises steadily to a maximum of 550 m., near Ras el Hillal, and then falls to 250 m. at W. Sudan. Once more it rises until, 5 km. beyond Barce, it has already reached 450 m. To the west of this point its exact altitudes cannot be known ; judging by the present maximum altitudes of the terrace and the top of the escarpment they must, however, have remained between 400 and 500 m.

No exact estimate can be made of the original undisturbed level of the shore-line, since no part of it is now horizontal. It can only be pointed out that the whole feature is clearly older than the lower

[1] The absence of any escarpment from the south side of the Gebel (Marinelli, 1920, p. 74) could be ascribed to the inhibition of marine erosion by the gentle initial slopes of the ground.

[2] A similar diagram constructed by Desio (1939, fig 13) is based on a rather small number of points, and is any case intended to illustrate no more than the present levels of the tops and bottoms of the escarpments.

escarpment, the latter having evidently encroached to varying degrees upon the upper terrace. If, therefore, the sea-level stood at 200 m. at the beginning of the formation of the lower escarpment, it is probable that it stood even higher during the formation of the upper terrace and escarpment.

3. *Chronology.*—The upper escarpment and shore-line are certainly post-Middle Miocene, and in view of their relationship to the lower escarpment they are probably pre-Pleistocene. In terms of world-wide geological time-scales there is no more to be said. It is possible, however, to compare the dates of these features with those of various tectonic structures of the Gebel, all of which are themselves post-Middle Miocene.

Already, indeed, it has been implied that the Martuba and Barce faults are older than the upper escarpment. In addition, it can easily be shown that the upper terrace truncates beds involved in the Benina-Tolmeita disturbance.

There is one other structure for which a similar comparison is possible : the El Atrun-Ghegab anticline. By a fortunate chance, Marchetti's map of the contours of the Lower Oligocene spring-forming marl covers a large part of the upper escarpment. Thus, the undulations of the " upper shore-line " can be compared with those of the underlying beds over a distance of about 150 km.

Such a comparison is made in Text-fig. 2, in which a line has been drawn showing the changing levels of the spring-forming marl when followed along the length of the escarpment. It should be pointed out that the levels used for the area east of Wadi Derna are approximations only, for Marchetti's strike-lines in this region terminate well to the north of the escarpment. It should also be mentioned that the level for the most easterly point was taken, not from Marchetti's map, but from observations made by Marchetti upon a spring at Umm Rzem, just beyond the point where the escarpment finally dies out. This spring was found to lie at 66 m. above sea-level and to issue from the Lower Miocene spring-forming horizon (Marchetti, 1938, pp. 116 and 118) ; if this horizon is still 60–70 m. above that of the Lower Oligocene, the latter would here be almost exactly at sea-level.

It can be seen from this diagram that the levels of the shore-line follow the undulations of the bedrock remarkably closely. Both lines attain their greatest heights at the same point, near Ras el Hillal ; both fall away gently on either side. On the western side the two lines are almost exactly parallel for a known distance of 60 km. East of the axis of folding the correspondence is less close, for the structural line begins to drop away more steeply,[1] but beyond Wadi en Naga the two

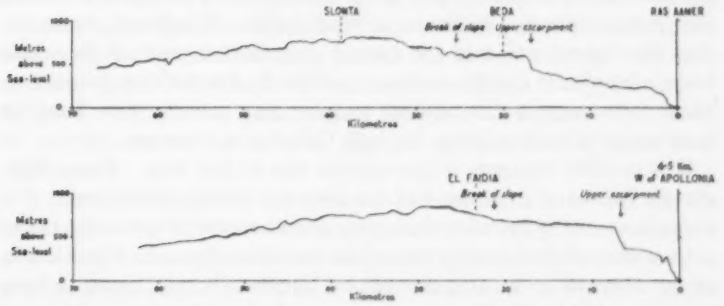
[1] This fact, easily verifiable on the ground, is the most direct argument against the escarpment being due to differential erosion.

lines, having reversed their original positions, again become roughly parallel. Here, admittedly, the structural line is somewhat erratic, but this may be due to the uncertainties mentioned above, or even to small-scale faulting.

Hence it appears that the upper shore-line was formed at a time when the El Atrun-Ghegab anticline, as such, did not exist; conversely, that the development of this anticline was solely responsible for the warping of the shore-line in the eastern Gebel. It also appears that some kind of structure must nevertheless have existed here even before the formation of the shore-line. Although at that time the beds on the site of the western limb of the anticline were still quite flat, the eastern limb already existed, in the form of a gentle monocline. This feature passed between Ras el Hillal and Wadi en Naga, and had a downthrow of about 300 m. to the south-east. Its general trend was perhaps similar to that of the present anticline.

IV. The High Gebel

1. *Description.*—Although much dissected by wadis, the highest part of the Gebel, above the upper escarpment, is an area of generally low



TEXT-FIG. 3.—Profiles taken north–south across the Gebel Akhdar, showing the escarpments and the break of slope of the high Gebel. Levels taken from the 1:100,000 maps. Vertical exaggeration: × 10.

relief and monotonous appearance (see Text-fig. 3). It consists essentially of gentle slopes falling away on either side of a crest-line which, though very ill-defined, can be said to run roughly from west-south-west to east-north-east, always within 25 km. of the escarpment. South of the crest-line these slopes continue into the dip-slope which extends downwards, apparently without a break, as far as the oasis depressions. On the north side the slopes of the high Gebel, until cut short by the escarpment itself, are broken only by one minor interruption, to be described below.

In spite of its low relief the area as a whole shows considerable variations of altitude (see Text-fig. 1, inset). There are two main areas of culmination, divided by a saddle. The higher of the two lies to the south of Cyrene and includes the highest point of the Gebel, 882 m. above sea-level. The other lies to the south of Barce, and reaches a maximum height of 676 m. near Gerdes el Abid. The saddle is situated in the vicinity of Tecnis, at altitudes between 400 and 500 m.

2. *Origins of present topography*

(*a*) *Effects of tectonic movements.*—It is safe to assume that the high Gebel has undergone relatively little subaerial erosion since the time when the upper escarpment and terrace were formed ; no more, at any rate, than these features themselves have undergone. Yet the area must have been affected by the earth-movements which distorted the upper escarpment. To some extent, therefore, its present topography must be a direct product of these movements.

As Desio has already indicated (1939, fig. 13), there is in fact a close correspondence between the undulations of the high Gebel and those of the upper escarpment. Both culminations of the Gebel lie near to parts of the escarpment which are particularly elevated, and the intervening saddle lies just to the south-west of the point where the escarpment sinks to a minimum at Wadi Sudan. It is found, moreover, that the highest point of the eastern culmination (and of the whole Gebel) lies almost exactly on the axis of the El Atrun-Ghegab anticline. These facts suggest that tectonic warping may actually have been the chief cause of such relief as the high Gebel now possesses.

It is possible to apply a quantitative test to this idea. From Marchetti's structural contours and the ordinary topographical maps, it is a simple matter to calculate the approximate summit-levels of the Gebel as they were while the upper shore-line was being formed. These levels, at any rate within the area covered by Marchetti's map, prove to have been remarkably regular, scarcely varying beyond the upper and lower limits of 250 and 200 m. above the sea-level of that time. The Tecnis saddle did not exist, and must therefore be wholly of tectonic origin. Already there was a slight culmination to the south of Cyrene, rising to about 330 m. above the contemporary sea-level, but even this has been greatly accentuated by later folding.

Beyond the limits of Marchetti's map, structural information is scanty and estimates of this kind become correspondingly unreliable. It is certain, nevertheless, that the original summit-levels must gradually have declined to the east of Derna. Westwards, beyond the Tecnis saddle, the present difference between the altitudes of the Gerdes el Abid culmination and of the upper shore-line south-west of Barce seems to be about 200 m., which suggests that the crest of the Gebel

may have maintained its uniform level in this direction ; the western culmination, as opposed to the eastern, may therefore be entirely due to tectonic uplift.

It thus appears that the Gebel, at the time of formation of the upper escarpment, was a long, low ridge, presumably an island, with a very even sky-line. Its topography, indeed, was even more monotonous than that of the high Gebel at the present day.

At this point the drainage pattern of the Gebel may be considered. Generally speaking, the main water-shed of the Gebel coincides with its crest-line, and the great majority of the wadis run directly towards the sea and towards the oasis depressions. Important exceptions are found only in the eastern Gebel, where a few wadis which eventually reach the Mediterranean run parallel to the crest-line for a part or the whole of their course. These facts suggest that the upper parts of many of the wadis may follow lines which have scarcely changed since the formation of the upper shore-line.

It is found, however, that not a single wadi, apart from a few minor head-streams, crosses the axis of the El Atrun-Ghegab anticline along the whole of its known length. The same is also true of a line drawn in continuation of this axis as far as the vicinity of Slonta, 60 km. south-west of El Atrun. There is in addition a very noticeable convergence of wadis upon the axis of down-folding at Wadi Sudan ; these, which include important wadis such as Wadi Kuf and Wadi Sudan, eventually combine to form the deep and wide gorge of Wadi Giargiarummach. Hence it is concluded that the late folding of the Gebel took place so rapidly as to be able to disrupt any pre-existing system of drainage.

(*b*) *Formation of original surface.*—It now remains to discuss the means whereby the high Gebel, as it existed at the time of the upper shore-line, had acquired its subdued relief. Its original surface is, of course, essentially that which is still visible, and as with the upper terrace bears no relation whatever to geological outcrops. In this case a still greater range of strata is transgressed, from Middle Miocene down to Cretaceous, and in addition several large-scale tectonic features are truncated. Once again, therefore, the surface in question cannot be structural. Almost certainly, in view of the rounded profile of its crest-line, the original relief of the high Gebel was primarily a result of very prolonged subaerial erosion at a time when the sea-level was relatively high.

Marinelli has pointed out, however, that there are certain places where a definite discontinuity in the seaward slope of the high Gebel can be observed (1920, p. 80). Desio, also, has noticed the existence of particularly level tracts of country lying immediately above the upper escarpment (1939, pp. 62–3). No definite conclusions were

drawn in either case, but these observations suggested to the present writer that even the high Gebel might not have escaped the effects of marine erosion.

Accordingly, a careful examination was made of the topography of the areas in question, as shown on the 1 : 100,000 maps. Owing to the dense network of wadis, little could be discovered by simple inspection. Numerous profiles were therefore drawn, at right-angles to the escarpment and extending inland as far as the crest of the Gebel.

By this means it was found that a distinct break of slope could indeed be traced, more or less continuously, between a point 2 km. north of Ghegab and a point about 40 km. to the west-south-west. Two typical profiles upon which the feature is visible are shown in Text-fig. 3. As can be seen, it is not a recognizable step, but merely a line along which, fairly abruptly, the seaward gradient of the Gebel slackens off. In plan it forms a smooth curve roughly parallel to the upper escarpment, the two features lying 10–13 km. apart. Its altitude, in so far as it can be measured, shows a steady rise from west to east, the levels at the two ends being about 575 m. and 725 m.

This again is not a product of differential erosion ; Marchetti's map shows that the inclination of the feature does not correspond with the dip of the underlying bedrock. A positive indication of its origin is provided by the topography of the area between it and the top of the upper escarpment. Apart from interruptions by wadis, the whole of this area has a seaward slope which is particularly regular, and, as Desio noted, very gentle ; gradients lie generally between 1 in 150 and 1 in 200, and one part of the area, south of Beda, is actually almost horizontal (see Text-fig. 3). These facts suggest that this is yet another wave-cut platform, and the break of slope another shore-line. Admittedly no actual cliff can now be seen, but this could perhaps be ascribed to intense subaerial erosion at the time when the platform was still submerged ; the water-table would have been high, and an underground drainage system might not yet have been initiated

In common with the other major features of the high Gebel, the break of slope must presumably be at least as old as the upper escarpment, and must therefore have been involved in the latest phase of folding. As with the upper shore-line, a rough estimate can be made of its disposition before the folding took place. It is found that the feature would then have lain almost horizontal, at a height of about 150 m. above the upper shore-line. This in itself provides confirmation for the marine theory. It also suggests two further conclusions : first, that the break of slope was formed at a time when sea level was perhaps as much as 350 m. higher than to-day ; secondly, that no considerable earth-movements took place between that time and the formation of the upper escarpment.

3. *Chronology*.—As was mentioned above, the surfaces of the high Gebel truncate a number of tectonic features. The clearest cases are those of the faulted monoclines of Gerdes el Abid and Mgiahir, neither of which seems to have the slightest effect on the landscape. The Barce and Martuba faults seem also to have been similarly truncated. All these structures must therefore be older than the erosion of the high Gebel.

In the case of the Benina-Tolmeita disturbance no direct evidence is available. The striking resemblance between this and the near-by tectonic lines of Barce and Gerdes el Abid suggests very strongly, however, that all three features may have been formed more or less simultaneously.

V. Conclusions

On stratigraphical and structural evidence, all that can be said concerning the history of the Gebel between Miocene and Pleistocene times is that certain earth-movements took place. As a result of the present geomorphological study it is believed, not only that certain other events can now be recognized, but also that some sort of order can be suggested for the earth-movements themselves. An attempt will be made below to present all these results in the form of a connected story.

(i) Throughout Early Tertiary times most of northern Cyrenaica was submerged, with a shore-line lying far to the south of the present coast (see Desio, 1935, figs. 55 and 56). Local non-sequences show, however, that it was already a somewhat unstable area.

(ii) The limited distribution of sediments later than Middle Miocene suggests that the main uplift of the Gebel began in Upper Miocene (Pontian) times. It is probable that all the known faults and monoclines of the Gebel were formed during this same period, in one single movement of subsidence towards what is now the seaward direction.

(iii) When these movements had ceased, the resulting irregularities were planed down by erosion; this, at any rate on the highest parts of the Gebel, was probably subaerial. Erosion was then continued by the sea, which must have stood at a very high level relative to the land, reaching to within 150 m. of the top of the Gebel. At this time the Gebel was undoubtedly an island.

(iv) While the land continued to be stable, the sea-level then dropped by about 150 m., whereupon marine erosion began once more, forming the upper escarpment and terrace. The Gebel must still have been an island, long, low and featureless.

(v) A period of broad folding followed, affecting all the higher parts of the Gebel. The El Atrun-Ghegab anticline assumed its present form, and some upward warping must have occurred in the regions south of

Barce. Between the two areas of uplift down-folding took place, along a line passing through Wadi Sudan and probably running to the south-west. These movements were responsible not only for the distortion of the upper shore-line but also for the present relief of the high Gebel and for much of its existing drainage-pattern.

(vi) When earth-movements had again died down, the sea, having dropped to a level perhaps a little less than 200 m. above that of to-day, again began to erode the land. This represents the first stage in the formation of the lower escarpment, and is believed to have occurred in earliest Pleistocene times.

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THE SEDGWICK MUSEUM,
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A New Genus of Echinoid from the Palaeozoic of Ireland

By Porter M. Kier

(PLATE I)

Abstract

A new genus and species of the *Lepidocentridae* is described from the Lower Carboniferous at Hook Head, Ireland.

Jackson (1912, pp. 403, 404) described a portion of an echinoid which he examined in the Sedgwick Museum, Cambridge, and identified as *Perischodomus biserialis* M'Coy. At that time only a small portion of the specimen was visible. At a later date the specimen was very skilfully cleaned by Mr. A. G. Brighton, and after the whole specimen was visible it was quite clear to both Brighton and Jackson that the echinoid was not *P. biserialis* but probably belonged to a new genus. Further portions of the specimens were cleaned by the author.

Family Lepidocentridae Loven

Eupholidocidaris gen. nov.

Type Species.—*Eupholidocidaris brightoni* sp. nov. from the Lower Carboniferous at Hook Head, Ireland. The type specimen, E10314, is in the Sedgwick Museum, Cambridge.

Diagnosis.—This genus is characterized by its moderately broad ambulacra with six columns of imbricating plates. These plates vary greatly in size, with the oral plates much larger than the aboral. The interambulacra are composed of eight columns of imbricating plates of equal size. Tubercles occur on most of the ambulacral and interambulacral plates.

Comparison with Other Genera.—This genus is similar to *Pholidocidaris* Meek and Worthen in having its oral ambulacral plates much larger than its aboral ambulacral plates. Furthermore, both genera have numerous columns of plates in their ambulacra and interambulacra. However, in *Eupholidocidaris* all the interambulacral plates of the different columns are of equal size, whereas in *Pholidocidaris* the adambulacral plates are much larger than the plates of the median columns. Furthermore, in *Eupholidocidaris* primary tubercles occur on the ambulacral plates, whereas they are absent on these plates in *Pholidocidaris*.

Eupholidocidaris is similar to *Meekechinus* Jackson in having tubercles on all its plates, but is dissimilar in having wide interambulacra. Also the ambulacral plates of *Meekechinus* are all of approximately the same size, whereas the oral ambulacral plates in *Eupholidocidaris* are much larger than the aboral. In a morphological series *Eupholidocidaris* lies somewhere between *Pholidocidaris* and *Meekechinus*.

Eupholidocidaris brightoni sp. nov.

Pl. I, Figs. 1, 2; Text-figs. 1, 2.

Description.—The specimen was probably once spherical, but was completely flattened during preservation. It is preserved as a slab 72 mm. long, 55 mm. wide, and only 8·5 mm. thick. Most of the plates of the specimen are present and it is possible to reconstruct their original arrangement. With the exception of one probable genital, nothing remains of the apical system.

Ambulacra.—There are six columns of ambulacral plates at the

TEXT-FIG. 1.—*Eupholidocidaris brightoni* sp. nov. Aboral view of the holotype, E10314, after second cleaning, showing the numerous small, irregularly shaped ambulacral plates, and the wide interambulacrum, composed of eight columns of plates.

mid-zone of each ambulacrum. Aborally and orally the plates are quite different. Aborally they are quite small and irregular and the pore-pairs are not in peripodium. The median column is composed of much larger plates than those found in the other columns. Because of the poor preservation of the specimen in this area it is not possible to determine the number of columns in the aboral portion. Orally the plates are very large, hexagonal, and equal-sized. Their pore-pairs are situated in large peripodia, with the pores separated by a median ridge. Most of the plates bear one large primary, perforate tubercle and a few secondary tubercles.

All the ambulacral plates imbricate orally and under the adambulacrals. The small, irregular aboral plates show evidence of much more imbrication than the oral plates.

EUPHOLIDOCIDARIS BRIGHTONI gen. et sp. nov.

Interambulacra.—At the mid-zone there are eight columns of thin scale-like plates in each interambulacrum. The plates are hexagonal and imbricate aborally, laterally, and over the ambulacra. The plates of the adambulacral columns are no larger than those of the median columns. Most of the plates of all the columns bear one large perforated tubercle. These tubercles are eccentric only when viewed on an isolated plate. When the plates are fitted properly on each other then the tubercles are in the centre of the exposed portion of each plate.

TEXT-FIG. 2.—Oral view of holotype showing large, regularly shaped ambulacral plates.

Locality and Horizon.—Lower Carboniferous limestone, Hook Head, County Wexford, Ireland.

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SEDGWICK MUSEUM,
CAMBRIDGE.

EXPLANATION OF PLATE I

FIG. 1.—*Eupholidocidaris brightoni* sp. nov. Aboral view of holotype, E10314, × 1, before second cleaning. Compare Text-fig. 1.

FIG. 2.—The same, in oral view, × 1. Compare Text-fig. 2.
(Drawings by Miss E. M. Talbot.)

On the Supposed Transformation of Tillite to Granite at Mount Fitton, South Australia

By G. A. CHINNER, M. SANDO, and A. J. R. WHITE

(PLATES II AND III)

ABSTRACT

The transformation of tillite to granite and gneiss by granitization has recently been postulated for rocks of the Mount Fitton area of South Australia. After examining the relationships in the field we have concluded that another interpretation is possible; the granites could be regarded as an older basement upon the eroded surface of which the tillites have been laid. The zone of feldspar rich rocks between the two could represent a basal arkose resting directly on the old granitic surface.

INTRODUCTION

MOUNT FITTON lies in the north-eastern extremity of the Flinders Ranges of South Australia, some 350 miles north of Adelaide. In this region, tightly folded slates and tillites of the Sturtian Series [1] are structurally underlain by a complex which includes granite, granite gneisses, and gneisses containing sillimanite, garnet, and cordierite (Sprigg, 1951).

In recent publications Dr. D. R. Bowes (1952, 1953, 1954) has maintained that the granitic complex is the product of granitization and basification of the tillite series. From an examination of the relationships between the complex and the tillite we consider that this interpretation is not the only one consistent with the evidence available and we are able to advance an alternative theory which is more in accord with present stratigraphical concepts in South Australia.

In this interpretation the underlying granitic complex is considered to have been metamorphosed and subjected to erosion before Sturtian times, and to have formed the land mass from which the tillites were in part derived. The zone of feldspar-rich rocks which overlies this complex is interpreted as a basal arkose composed predominantly of disintegrated fragments and boulders of granite resting upon the eroded surface of the older rocks. This basal arkose grades upwards into " normal " tillite with a matrix near greywacke in composition. These relationships have been obscured in places by post-tillite metamorphism involving the recrystallization of the sediments and the development of chlorite and biotite, and by intense shearing along parts of the contact.

[1] Part of the Adelaide System (Later Pre-Cambrian).

The junction between tillite and complex may thus be regarded as a stratigraphic unconformity.

The " Transition " from Tillite to Granite

As both Sprigg and Bowes have indicated, the boundary between the tillites and the granitic complex has in most places suffered considerable shearing, so that much of the actual contact is obscured.

In some localities, however, the contact does not appear to be sheared, and one of these Bowes (1954, p. 463) has chosen as the " type area " for granitization, discussing in detail the stages in the transition from " normal " tillite to the coarse porphyritic granite which forms the bulk of the complex in the locality.

In the field this " transition " may be readily traced. Outcrops of tillite about 100 yards from the contact (Bowes' " stage 2 " of granitization) contain erratics of fine-grained granite and quartzite, in addition to an abundance of feldspar crystals, some showing crystal outlines, some rounded and some angular. Porphyritic granite lithologically resembling the granite in the complex may also be seen in rounded or subrounded forms. Usually weathering effects, combined with the irregularity of the exposed surface, render the interpretation of such forms difficult ; in certain outcrops, however, they may be recognized as undoubted erratics. Plate II shows a photograph of such an erratic in an outcrop just west of the " type area "; it may be compared with a photograph (Bowes, 1953, plate x, fig. 3) of the porphyritic granite from the complex.

In thin section these rocks show a fine-grained matrix of recrystallized quartz, chlorite, and biotite in which are set abundant crystals of quartz and feldspar ranging up to several centimetres across ; they may be rounded or angular. Many of the larger feldspars (both plagioclase and microline) contain inclusions of quartz or biotite ; some of them are intensely sericitized, while others are quite fresh.

Closer to the contact the proportion of feldspar increases until the rocks are predominantly quartz-feldspar aggregates (Bowes' " quartz feldspar migmatite "), bearing little resemblance to normal tillite. The fine-grained pelitic portion, seen in the groundmass of " normal " tillite, is here virtually absent ; the rock consists of a heterogeneous mass of quartz and feldspar individuals of all sizes and shapes. The feldspars are again in all stages of decomposition.

At the contact this quartz-feldspar rock rests on coarse-grained porphyritic granite of the complex. There is a marked lithological contrast between these two rock types, so that although the actual junction is not exposed its position can be determined to within a few feet.

The quartz-feldspar rocks are regarded by Bowes as the products of the feldspathization of rocks similar to the greywacke type tillites above them ; the replacement textures and quartz-biotite inclusions prominent in the large feldspars are regarded as evidence of their growth as replacements of a finer-grained matrix. However, feldspars in the granites of the underlying complex display similar "replacement" textures, textures which are not rare in feldspars of granitic rocks. They would thus be found in sediments derived from such rocks and would appear as individuals similar to those in the "feldspathized" tillites. Certainly the shapes of many microclines in these rocks are suggestive of a clastic origin.

To illustrate this point, in Plate III, fig. 1, we have reproduced (by kind permission of Dr. Bowes and the Geological Society of London) Bowes' (1954) plate xxiv, 1, showing "feldspathized" tillite. A microcline individual has been outlined to show its rounded form ; it may readily be interpreted as a pebble included in the tillite. Part of a feldspar from the granite of the complex is shown in Plate III, fig. 3. If eroded from the granite and included as a pebble in a sediment, this would give an individual similar to that in the tillite of Plate III, fig. 1.

The supposed evidence of progressive granitization which has aroused so much interest (Bowes, 1954, discussion) may thus be readily reinterpreted if the quartz and feldspar crystals in the "migmatites" are regarded as clastic, the larger ones being pebbles or erratics derived from the underlying granites. The increased proportion of feldspar (increase of Si, Na, and K, and the decrease in Fe, Mg, Ca, Ti, P, Mn) as the granite is approached, represents an increase in granite debris in the sediment. The textures within these feldspars are presumably metamorphic but they may be regarded as relics of a pre-tillite metamorphism rather than products of the metamorphism of the tillites themselves.

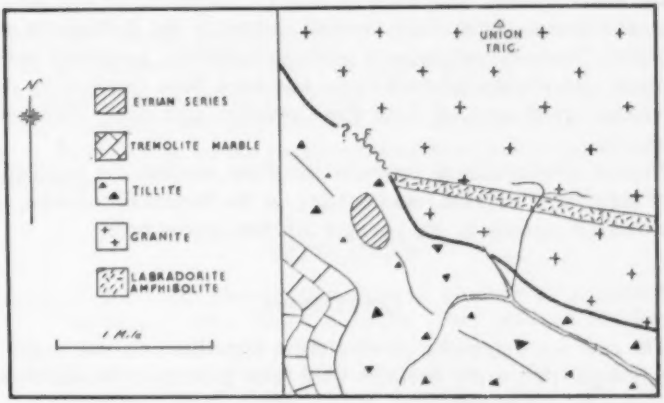
In our opinion, these so-called feldspathized tillites show no features foreign to a coarse grit composed of detrital quartz, feldspar, and granite fragments : a rock of this composition would be expected to form at the initiation of sedimentary deposition on a granitic land surface.

"Relict Structures" or "Ghost Stratigraphy" in Rocks of the Complex

Directional features, no doubt representing metasedimentary structures, have been mapped by Bowes as being parallel to the form lines in the tillite series, and interpreted by him as relict structures of this series ; this has presumably been taken as evidence of the original conformity of complex and tillite series.

It may be demonstrated, however, that general conformity of structure is perfectly compatible in two unconformable sequences. As Lees (1952) has recently emphasized, folding in cover strata often passively follows an earlier folding of the basement ; it is therefore possible that the orogenic forces active during folding of the tillites were similar to those which originally deformed the basement, resulting in a general similarity in structural trend between overmass and basement rock.

In this regard, however, we are able to make a small correction to the published map (Bowes, 1954, p. 457). One mile south of Union trig. a band of " basified tillite " (a massive labradorite amphibolite) marked as trending parallel to the strike of the adjacent tillites (120° T) was measured by us as trending at 100° T ; the rock may in fact be followed in dyke-like form to the edge of the granite complex, although there is no trace of it in the tillites outside (Text-fig. 1).



TEXT-FIG. 1.

The view that the fine-grained granitic rocks are granitized Sturtian quartzites and that the hornblende-labradorite rocks are basified tillites has no firm foundation, for in no place has a single bed been traced from its unaltered state in the tillite series into its " granitized " form in the complex. Bowes himself states (1952, p. 14) : " It has not been possible to trace all the successive stages of granitization in one quartzite band within the migmatite complexes, and the following series of changes is that deduced from a general study of the transformed quartzites." We therefore consider that whatever the origin of these fine-grained granites and hornblende-labradorite rocks, their occurrence provides no evidence to support the contention that the complex in which they are found is transformed tillite series.

The Possibility of an Unconformity

Mawson (1912) and Campana (1954, 1955) have demonstrated that in the Olary–Broken Hill region (N.E. South Australia) the older Pre-Cambrian basement is overlain by later Pre-Cambrian sediments of the Adelaide System. In areas where this system is very thick the Sturtian tillites may be underlain by thousands of feet of sediment, but in this area of axial culmination the glacial deposits rest directly upon the older basement, the basal beds bearing a considerable resemblance in composition to their underlying parent rocks (Leslie and White, 1955.)

A similar culmination is considered by Sir Douglas Mawson [1] and Mr. R. C. Sprigg [1] to occur in the Mount Painter–Mount Fitton area, although post-Sturtian metamorphism has rendered its recognition difficult. Dickinson and Sprigg (1953) have referred to this as the " Paralana nucleus " and state (p. 430) : " Remnants of very ancient crustal elements occur along the east margin of the Adelaidean geosyncline. They are complexes of prolonged stability, composed of acid igneous and metamorphosed rocks and have been overlain by only moderate thicknesses of Late Pre-Cambrian and Early Palaeozoic rocks."

Present stratigraphical concepts therefore support the contention that older Pre-Cambrian rocks outcrop in the Mount Fitton area, and are overlain directly by the younger Sturtian glacial beds.

Conclusions

The case for suggesting an alternative hypothesis for the origin of the feldspar-rich rocks between tillite and granite at Mount Fitton may thus be summarized:

1. The form lines within the tillite series follow the trend of the contact with the underlying complex : thus the contact lies approximately on one stratigraphical horizon and in no place has any particular bed been traced along its strike into the metamorphic complex.

2. The occurrence, as boulders in the tillite, of the distinctive porphyritic granite of the complex suggests that this granite formed part of the land surface from which the glacial deposits were derived.

3. It is probable that this region is one of axial culmination in the Adelaide System, so that the older Pre-Cambrian rocks could be expected to outcrop.

Thus the rocks interpreted by Bowes as feldspathized tillites may be equally well explained as arkosic grits representing the disintegration

[1] Personal communications.

products of the granite on which they lie, and as forming the base of the tillite formation.

From our observations in the Mount Fitton area, therefore, we think that Bowes has by no means proved that the granitic complex has been derived even in part by the transformation of the tillites and associated sediments of the Sturtian Series; we consider the boundary between tillite and complex more likely to be a sedimentary than a metamorphic one. We have published our views as an indication that Bowes' conclusions as to the nature of the supposed transformation process must be regarded with caution.

ACKNOWLEDGMENTS

We should like to thank Dr. D. R. Bowes for his assistance and in particular for providing us with a manuscript copy of his work then in the press.

For their interest and discussion we are also grateful to Professor Sir Douglas Mawson, Professor A. R. Alderman, and Mr. R. C. Sprigg, of Adelaide ; to Dr. A. K. Wells and Mr. R. W. D. Elwell, of King's College, London ; and to Professor C. E. Tilley, Dr. S. O. Agrell, and Dr. S. R. Nockolds, of the Department of Mineralogy and Petrology, Cambridge.

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EXPLANATION OF PLATES II AND III

PLATE II

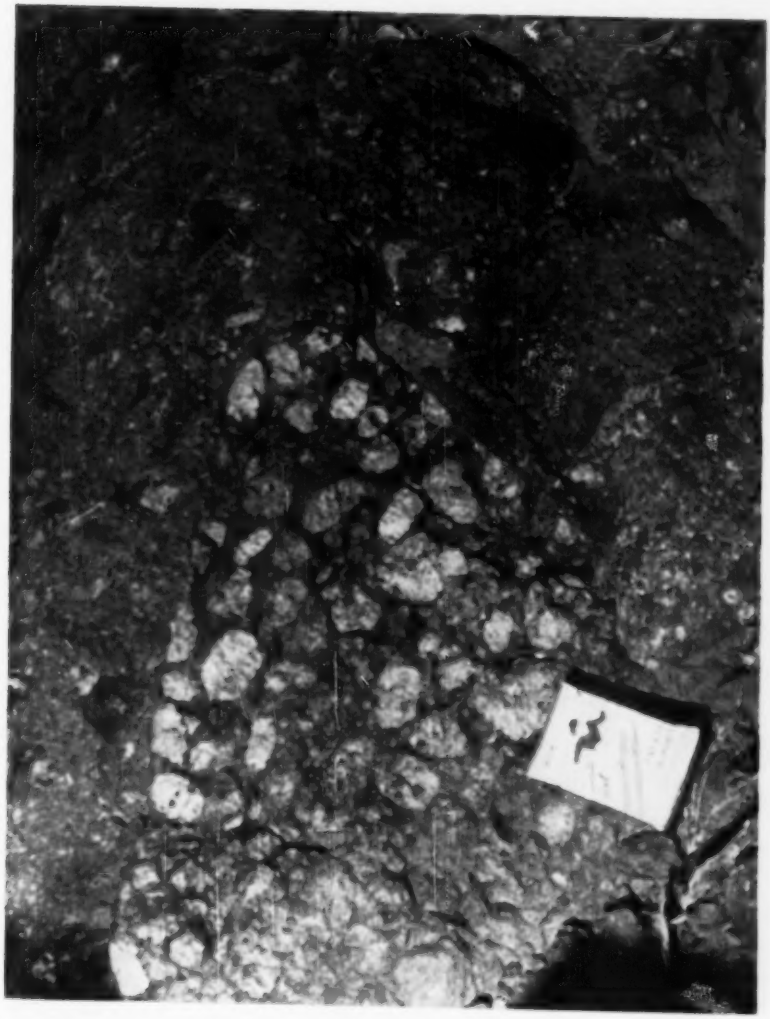
Erratic of porphyritic granite in so-called " feldspathized " tillite. Compare Bowes' (1953), plate x, fig. 3, of porphyritic granite from the complex.

PLATE III

FIG. 1.—Bowes (1954) plate xxiv, fig. 1, described as " feldspathized tillite showing the development of potash-feldspar crystals at the expense of the quartz-biotite matrix ".
The outlined microline individual may be interpreted as a pebble. Crossed nicols. × 16.

FIG. 2.—Enlargement of microcline individual of Fig. 1. Crossed nicols. × 30.

FIG. 3.—Photomicrograph of porphyritic microcline from the granite of the complex showing quartz inclusions along cracks and veins in the crystal. Compare Fig. 2. Crossed nicols. × 26.



BOULDER OF PORPHYRITIC GRANITE IN TILLITE, MOUNT FITTON, SOUTH AUSTRALIA.

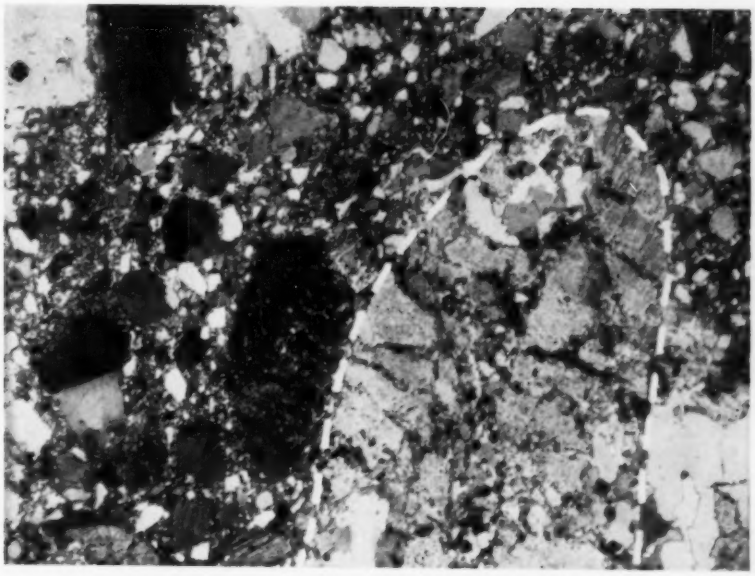


FIG. 1.

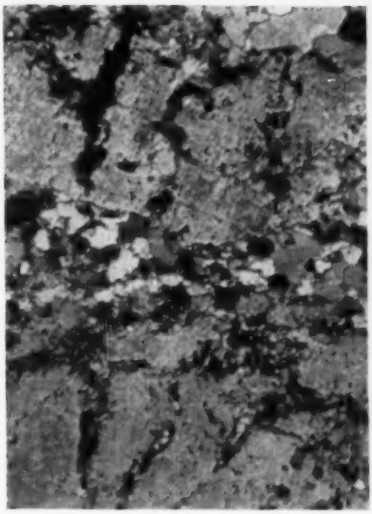


FIG. 2.

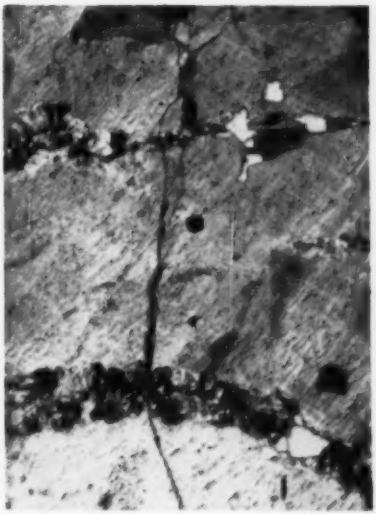


FIG. 3.

FELDSPARS IN TILLITE AND GRANITE, MOUNT FITTON AREA.

Corundum from Ceylon

By A. J. Wells

Abstract

The origin of precious corundum found in the gem-bearing gravels of Ceylon has long been unknown. An occurrence of sapphire is described from a contact zone where syenite has been intruded into, and desilicated by, crystalline limestone. The process of desilication in such contact zones is considered capable of accounting for much of the gem-quality corundum of the island.

Introduction

THE island of Ceylon is formed mainly of regionally metamorphosed ortho- and para-gneisses, with intrusive granitic rocks, and is a geological continuation of the Archaean complex of South India. About nine-tenths of the island is covered by these crystailine rocks, only small areas of which have so far been studied in any detail. They have been divided into two series by Fernando (1948), who recognizes para-gneisses (and associated granitic intrusives) of the Khondalite Series overlying intruded ortho- and para-gneisses of the Vijayan Series. The former includes numerous bands of crystalline limestone interbedded with quartzites and granulitic rocks.

Ceylon has long been famous for its gem industry, which is of great antiquity. First place in the very comprehensive list of gems found in the island must be given to the varieties of transparent corundum, all of which (except the red ruby, which is rare in Ceylon) are loosely referred to as sapphire. But by far the most important and valuable of these are the true blue sapphires. These gems are all obtained from placer deposits in alluvial tracts on the Khondalite Series, around Ratnapura in the south-western part of the island. Although some of the stones retain their crystal outline almost unscathed, many are considerably water-worn, and they have evidently been collected together in these alluvial deposits from a wide area. The origin of these sapphires has always been of great interest and importance to the gem industry, and countless attempts have been made to discover their parent rock. There is a legend that a few exposures of precious corundum in situ were at one time known, but that they were so skilfully concealed from the invading Portuguese four centuries ago that the Singhalese themselves were unable to rediscover them. There is certainly no present record of any outcrop from which gems of the quality found in the placer deposits are likely to have been derived. But with the spread of geological knowledge after the beginning of the last century the search was intensified. As it was known that the renowned rubies from the Mogok area of Upper Burma were found in

bands of crystalline limestone in a gneissic Archaean complex similar to that of Ceylon, it was naturally in the limestone bands that most of the searching was done. But this work was entirely fruitless, and attention was eventually transferred to other rocks of the complex, again with little success. It must have been suspected, even then, that the paragenesis of these sapphires was different from that of the Burma rubies (sapphires have also been found in Burma, where they are much less common than rubies, and are said (Adams, 1926) to occur in a granular microperthitic rock), and it is now known that although rubies are generally found in metamorphic rocks, most occurrences of sapphire are connected with igneous intrusions.

Previous Records of Corundum

The first record of corundum in situ in Ceylon was by Coomaraswamy in 1903. He found hexagonal prismatic blue sapphires in a thin band of decomposed feldspathic granulite near Kandy, but they were useless as gems due to their opacity and well developed rhombohedral parting. In the following year the same author described fallen blocks of weathered corundum-sillimanite rock collected from the Haputale escarpment near the Balangoda–Haputale road. The corundum here was in tabular hexagonal violet crystals which were also opaque and useless as gems. Coates (1935) recorded the first discovery of transparent corundum from a pegmatite in decomposed granulite near Matara. They were not suitable for gems because of their well developed parting, hexagonal prismatic crystals up to an inch long breaking up into small fragments when washed out of their matrix. Coates also mentions an occurrence of pale blue corundum in a lens of decomposed feldspar apparently connected with a pegmatite vein on the edge of Horton Plains. But here again the crystals broke into fragments when detached, and were generally cloudy.

Descriptions of the above four occurrences constitute the only positive knowledge on the source of Ceylon corundum. But in each case the rock was decomposed and the corundum not capable of contributing much to the mineral wealth of the island. As the value of gems found in alluvial deposits of the Ratnapura district now runs to several million pounds, it is evident that theories on the origin of these valuable stones have suffered from lack of local evidence. Since the discoveries of Coates, however, it has been considered that pegmatite veins were the most likely source of precious corundum. In the latest synthesis of Ceylon geology, Fernando (1948) states that although the primary sources of the precious and semi-precious stones are unknown, with but few exceptions there is little doubt that they are derived from pegmatite veins.

New Corundum Localities

During the course of a recent field season in Ceylon, the writer located the outcrop of the corundum-sillimanite rock described by Coomaraswamy, and also was fortunate in discovering a new corundum locality where gem-quality sapphire has developed along the contact of a syenite intrusion into a limestone band of the Khondalite Series. Brief details of these occurrences are now given.

(*a*) *The Corundum-sillimanite Rock.*

Loose blocks of this unusual rock were discovered by Coomaraswamy on Kalupahana and Haldumulla estates on the Haputale escarpment. It was much weathered and friable, consisting mainly of flat hexagonal tabular violet crystals of corundum up to 2 cm. in diameter, and sillimanite in aggregates and idiomorphic crystals as much as 5 cm. in length and 2·5 mm. in cross-section. By tracing the resistant corundum crystals in the soil up the escarpment, the outcrop of this rock was located on the south face of Batgoda, above the north-east corner of the Needwood group of estates, and some 400 feet below the level of Idalgashinna station on the crest of the slope. The corundum-bearing rock extends for about 50 feet along the strike, has a maximum thickness of 15 feet, and occurs interbedded with partially amphibolized pyroxene-garnet-granulite of a type common in the Khondalite Series. The violet corundum crystals are always tabular and opaque, with the well developed basal planes frequently striated in three directions intersecting at 60°. They generally do not exceed 3–4 mm. in diameter, but there is a localized patch of about one square yard in the centre of the outcrop where they reach 2 cm. in diameter. The corundum crystals account for about 20 per cent of the rock, and contain numerous small inclusions of ilmenite and rutile. They are enclosed in a matted aggregate of sillimanite needles with very well developed cleavage and a positive optic axial angle of 25°.

The corundum-sillimanite rock passes eastwards along the strike with increasing silica content into a friable white quartz-sillimanite-rutile rock. The sillimanite, making about 70 per cent of the rock, encloses very many deep red prismatic rutile crystals between 0·1 and 0·5 mm. in length, and is set in a groundmass of quartz. But westwards the passage from the corundum-sillimanite rock is characterized not only by an increase in available silica but also by the incoming of magnesia and iron. This leads to the addition of cordierite, almandine garnet, and pleonaste to the assemblage, the latter being so nearly opaque in microsections that it is only on very thin edges that its green colour can be seen. Corundum is only very sparingly present here and disappears entirely at the western end of the exposure with the

incoming of quartz, plagioclase, and pyroxene, and the exit of cordierite, sillimanite, and pleonaste. There is thus a passage both along and across the strike into the normal pyroxene-garnet-granulite, and it is probable that the high concentration of alumina at this horizon was caused by removal of other oxides during a period of lateritic weathering, corundum being formed in a localized bauxitic deposit during regional metamorphism. Corundum formed in this way is apparently always opaque and tabular in habit, crystallizing during metamorphism in the form often assumed by ruby. As corundum is unlikely to occur in other habits in the bulk of the granulite, this is evidently not the parent rock of the precious corundum in the placer deposits, which is always in prismatic and steep pyramidal crystals with the familiar barrel shape.

(*b*) *The Sapphire-bearing Syenite-limestone Contact.*

A petrological survey of rocks of the Khondalite Series in a small area around Non Pareil estate (66 miles east-south-east of Colombo and 38 miles south-south-east of Kandy) included a study of a band of crystalline limestone in a series of para-gneisses consisting mainly of pyroxene-garnet-granulites and sillimanite-bearing quartzites. An almost complete section through the limestone occurs in a narrow and very steep unnamed mountain stream (a right bank tributary of the Kiriketi Oya) beneath World's End Drop, where the band is between 130 and 150 feet thick. The upper contact of the limestone is exposed in this stream where it crosses the jungle track from Non Pareil to Ohiya, some 350 yards beyond the upper limit of the tea in the upper division of Non Pareil estate, at a height of about 5,190 feet. Coarse-grained dolomitic marble with forsterite, diopside, and phlogopite, accompanied by accessory chondrodite, spinel, apatite, pyrite, and graphite, is exposed for 60 feet below the track. A narrow but continuous section in the stream between 60 and 85 feet below the top of the limestone exposes part of a syenite intrusion. This is its only visible outcrop, there being impenetrable jungle on either side of the section. The limestone is everywhere separated from the syenite and its derivatives by a continuous thin zone of pale green phlogopite between 5 and 20 mm. thick. Near the contact the limestone contains up to 5 per cent of pyrite, but is otherwise unaltered.

The syenite is a pale grey coarse grained feldspar rock, with a few scattered small green pyroxenes in a complex microperthite in which both orthoclase and microcline have exsolved plagioclase (oligoclase-andesine). The orthoclase is characterized by a low birefringence of 0·004, and a very low negative optic axial angle of about 35°–40°. Quartz is present in small scattered clear rounded blebs in the micro-

perthite, and accessory minerals include calcite, apatite, sphene, and zircon. Towards the junction with the limestone, the syenite loses its quartz, and encloses irregular areas of diopside-scapolite rock thought to be partly digested inclusions of limestone. These are composed of about 30 per cent of pale green diopside (locally replaced by tremolite) and 65 per cent of scapolite, the latter giving a greasy grey-green appearance to the rock. The scapolite shows good cleavages at right angles in basal sections, which have a tendency to hexagonal outline. N_ω was measured as 1·579 (± ·002), indicating a composition of Ma_{37} Me_{63} (Winchell, 1951). The syenite near the limestone also develops a variable proportion of separate granular plagioclase (Ab_{85} An_{15}) in place of some of the microperthite. These crystals show undulose extinction and distortion of the twin lamellae due to dynamic action. There are many thin strings of calcite in cleavages and cracks in the microperthite. Also developed near the contact are areas of irregular replacement of the microperthite. The replacing mineral, locally making 10 per cent of the rock, is colourless, entirely anhedral, and has its optic axis parallel to the junction. It is uniaxial negative, with birefringence 0·003 (N_ε — 1·539, N_ω — 1·542). With these optical properties, it was mistaken for a soda-rich nepheline until a negative result was obtained with a staining test for feldspathoids. It is now evident that the replacement is by an unusual soda-rich scapolite containing about 85 per cent of the marialite molecule.

Modification of the intruding syenite is most pronounced in places along the immediate junction where the limestone has caused desilication to such an extent that corundum has formed. This corundum-bearing rock, between the phlogopite zone and the normal syenite, is a nodular rather than a continuous development. It occurs up to about 3 feet in thickness, and has formed at the contact where the inclusions of diopside-scapolite rock in the syenite are more abundant than elsewhere. It is a white compact fresh feldspar rock containing up to 15 per cent of conspicuous blue and blue-green hexagonal prismatic and steep pyramidal crystals of corundum, many of which are over 1 cm. in length and of the typical barrel shape, often with horizontal striations on the crystal faces. They are strikingly similar in colour and detail of habit to the crystals recovered from gem gravels some 20 miles to the south-west. A high proportion of these sapphires are clear and of good gem quality, but a few are flawed by a rhombohedral parting. In microsections they are pleochroic, and sometimes show polysynthetic twinning. But there are in addition straggling patches of corundum devoid of any crystal outline, which are intimately associated with pale mauve spinel. These, together with a little calcite and scattered flakes of pale brown phlogopite, are enclosed in a granular aggregate of well twinned plagioclase (oligoclase-andesine), which

has suffered local partial alteration to scapolite, and which contains widespread but small aggregates of very finely fibrous sillimanite. The latter tend to be more common in the immediate vicinity of the corundum, but are strikingly absent near patches of spinel. Isotropic analcite (from plagioclase) and apatite are also sparingly present. There is evidence of post-consolidation dynamic action in the bent, broken and re-welded fragments of twinned plagioclase.

Desilication and the Formation of Corundum

A number of sapphires of potential value were collected from this exposure beneath World's End, although it is of severely limited size. And it is clear that the process which gave rise to their formation is capable of producing corundum of gem quality. In this instance, the bulk of the limestone has been effectively sealed off from the intrusive syenite by the phlogopite zone, which has taken potash from the orthoclase of the intrusion, and consequently enriched the marginal material in plagioclase. Silica has replaced volatile CO_2 in the inclusions of carbonate, with the formation of diopside. The syenite magma itself did not contain an abnormal quantity of alumina, and it is the removal of silica from it by reaction with xenoliths rather than any addition of alumina which has led to the very localized production of corundum. This occurrence is similar in many ways to a corundum-aplite from Natal described by du Toit (1918). He records a quartz-orthoclase-plagioclase pegmatite which is modified to an oligoclase-corundum rock where it cuts through serpentine, a zone of phlogopite and talc forming along the contact. This apparent one-way reaction is due to the replacement of water in the serpentine by silica and potash from the pegmatite. Some of the corundum is barrel shaped and irregularly sapphire-coloured.

It must be emphasized that desilication of this type will only produce corundum in restricted quantity, and is a somewhat different process to that which leads to relatively large-scale formation of corundum in pegmatites and other rocks often associated with alkaline nepheline syenites. Well-known examples of the latter have been described from Madras (Holland, 1901) and Ontario (Adams and Barlow, 1910), where the corundum has been attributed to primary crystallization from a magma abnormally rich in alumina, but which it is now suspected may be of metasomatic origin. This " magmatic " corundum is rarely, if ever, of value as gem material, and it is evident that if the precious sapphires of Ceylon are to be found in pegmatites, they will only occur where the magma has cut through a rock such as limestone, which is capable of absorbing silica from the pegmatite in exchange for a volatile constituent. The necessary conditions will also be satisfied

along other syenite-limestone contacts, which should therefore be regarded as potentially sapphire-bearing. It is probably because of very poor exposures due to lateritic weathering and dense jungle cover rather than rarity of such contacts that they have escaped detection for so long. The weathering of a very modest number of them could produce the quantity as well as the quality of material required, and it is suggested that much of the sapphire recovered from the gem gravels of Ceylon has been derived from the contact zones of acid intrusions into limestone bands of the Khondalite Series.

The author is indebted to Mr. L. J. D. Fernando (Ceylon Government Mineralogist) for affording laboratory facilities in Colombo, and to Mr. and Mrs. D. Boyd-Moss for generous hospitality in the field.

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The Supposed Moinian Basal Conglomerate at Glen Strathfarrar, Inverness-shire.

By JOHN G. RAMSAY

ABSTRACT

At various localities along the contact of the Moine Series with the supposed Lewisian Inlier at Glen Strathfarrar structures resembling those of a conglomerate have been described. New evidence is brought forward which suggests that these structures are of tectonic origin and were produced by the disruption of competent bands in an incompetent matrix.

INTRODUCTION

THE Moine Series, a group of metamorphosed sediments and igneous rocks, outcrops over a large part of the Northern Highlands of Scotland. In the past certain tracts of altered sedimentary and igneous rocks within the Moine Schists have been distinguished from the surrounding rocks, correlated with the Pre-Cambrian Lewisian rocks found to the west of the Moine thrust, and interpreted as stratigraphical inliers of Lewisian gneiss in the Moine Series. At various localities near the contact of the Moine Schists with the Lewisian inliers, conglomeratic structures interpreted as a basal conglomerate have been described. Such structures were first recognized at Glenelg by Clough (1900, and in Peach and others, 1910) and later at Attadale, Scardroy, and Glen Strathfarrar. Of these occurrences three have been examined in recent years. Bailey and Tilley (1952) have reaffirmed the belief that those at Glenelg and Attadale are true conglomerates, but Sutton and Watson (1953) have argued that the Scardroy Lewisian inlier probably forms part of the Moine Series and have given reasons for suggesting that the supposed Moinian basal conglomerate is not a genuine conglomerate but an augen gneiss. In the course of the discussion following the paper of Sutton and Watson, Tilley remarked :

> " But perhaps of all the evidence that which most required reassessment was that provided only a few miles from Scardroy in the Glen Strathfarrar inlier where Dr. E. M. Anderson had described basal conglomerates which had been traced for more than a mile along the margin of this inlier. Were these in reality basal conglomerates such as those described by Clough and Peach at Glenelg and Attadale ? "

During the last two years a detailed study has been made of the Glen Strathfarrar area, in the course of which the rocks described as basal Moinian conglomerates have been re-examined. The author hopes to give a detailed account of this work elsewhere The purpose of this

present paper is to bring forward evidence which suggests that the conglomerate is, in fact, of tectonic origin and that it does not lie at the base of the Moine Series in Glen Strathfarrar.

History of Research

In 1900 Hinxman began mapping the Glen Strathfarrar district and described banded granitic and granulitic biotite and hornblende gneiss which

> "... probably forms part of the large mass of Lewisian gneiss mapped to the north of the River Meig," i.e. the Scardroy inlier (Hinxman, 1901).

In 1904 a detailed investigation of the Glen Strathfarrar Lewisian inlier was begun by E. M. Anderson (1905). Hornblende schists and gneisses with occasional bands of actinolite schist and acid bands representing sheared pegmatites characterize the supposed Lewisian rocks. The following year Dr. Anderson discovered altered sediments in the rocks of Lewisian type including crystalline limestones, calc-silicate rocks, and graphitic mica schists. At various localities along the south-eastern margin of the Glen Strathfarrar inlier:

> "... a formation is found at the base of the Moine Series which much resembles a sheared conglomerate. The fragments .... consist for the most part of siliceous material probably derived from the more acid portions of the adjacent complex gneiss." (Anderson, 1906.)

In 1913 the Central Ross-shire Memoir and sheet 82 of the Geological Survey of Scotland were published (Peach and others, 1913). Detailed descriptions of the supposed basal conglomerate were given by Crampton and Anderson. The best examples of these structures were described by Anderson along the eastern and south-eastern margins of the inlier :

> " Where best developed, rounded, oblong or elliptical blocks of siliceous rock are enclosed in a more micaceous matrix. The blocks consist partly of quartzite, and partly of siliceous granulite containing a small amount of mica ; their elongated form is evidently a result of shearing movements." (Anderson, in Peach and others, 1913, p. 67.)

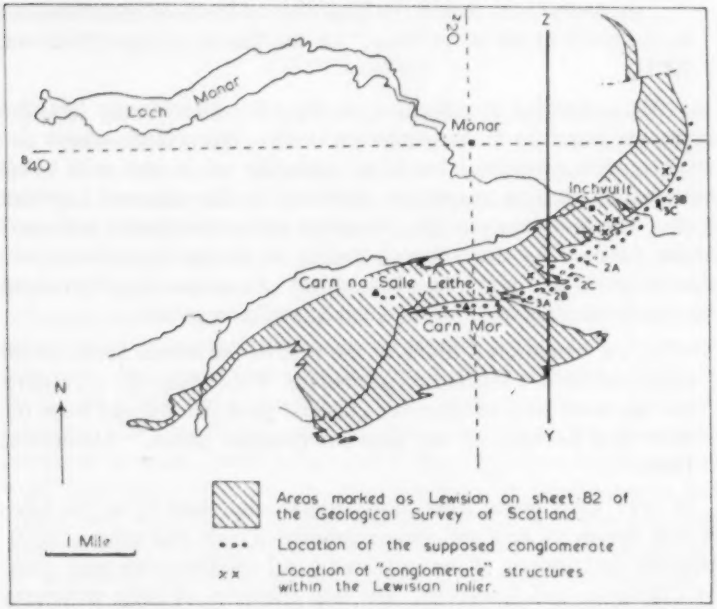
The absence of included fragments of hornblende schist and other characteristic members of the Lewisian complex was explained by supposing that these types were less resistant than the siliceous types :

> "It is doubtful whether any pebbles still remain that have been derived from the hornblendic portions, the more finely divided

material from the latter being more likely to enter into the composition of the matrix." (Anderson, 1906, p. 109.)

". . . pebbles of these substances originally present in the conglomerate, have become unrecognizable under the shearing movements. They may perhaps be represented by certain irregular micaceous patches in the groundmass." (Anderson, in Peach and others, 1913, p. 67.)

In one place Anderson described an epidotic matrix to the conglomer-



TEXT-FIG. 1.—Map showing the position of Glen Strathfarrar "Lewisian inlier". National grid reference lines are shown as broken lines. The numbers and letters refer to the location of the illustrations shown in Text-figs. 2 and 3.

ate which suggested a comparison of these Moine rocks with the epidotic grits at the base of the Torridonian Series. (Anderson, 1906; and in Peach and others, 1913, p. 67.)

Crampton (1906; and in Peach and others, 1913, p. 41) described another occurrence of a supposed basal conglomerate on Carn na Saile Leithe about two miles to the west of that described by Anderson:

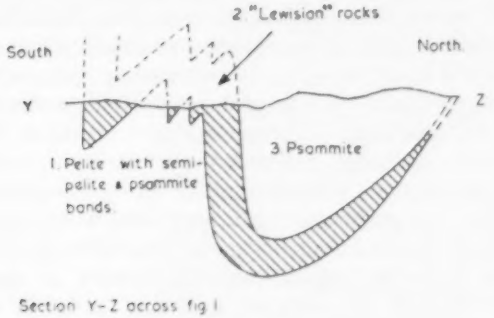
". . . lenticular patches of a conglomeratic rock rest upon the gneiss. These patches follow the same line of strike as the band of con-

glomeratic rock which crosses Carn Mor, farther east. . . . The rock is of a highly siliceous Moine type, containing what appear to be drawn-out fragments and pebbles of pegmatite " (in Peach and others, 1913, p. 41).

These patches of supposed conglomeratic rock have been omitted from sheet 82 but were shown as Moine outliers on the 6 in. to 1 mile field sheets (Inverness-shire sheet 15).

The New Evidence

The rocks within the supposed inlier consist for the most part of hornblende and biotite granulites and gneisses with frequent calc-silicate bands. The Survey Officers thought that these rocks occupied the core of an anticlinal fold and that they represented an upfold of the Lewisian basement. The rocks on either side of the " Lewisian inlier " are, in fact, different in character, those to the north-west of the " inlier " are psammitic granulites, whilst those to the south-east are pelitic schists and gneisses with semi-pelitic and psammitic bands. The marked differences in character of the rocks on either side of the " inlier " would appear to cast doubts on the suggestion that the supposed Lewisian rocks occupy a fold core. A detailed structural



Section Y–Z across fig 1

Text-fig. 1a.

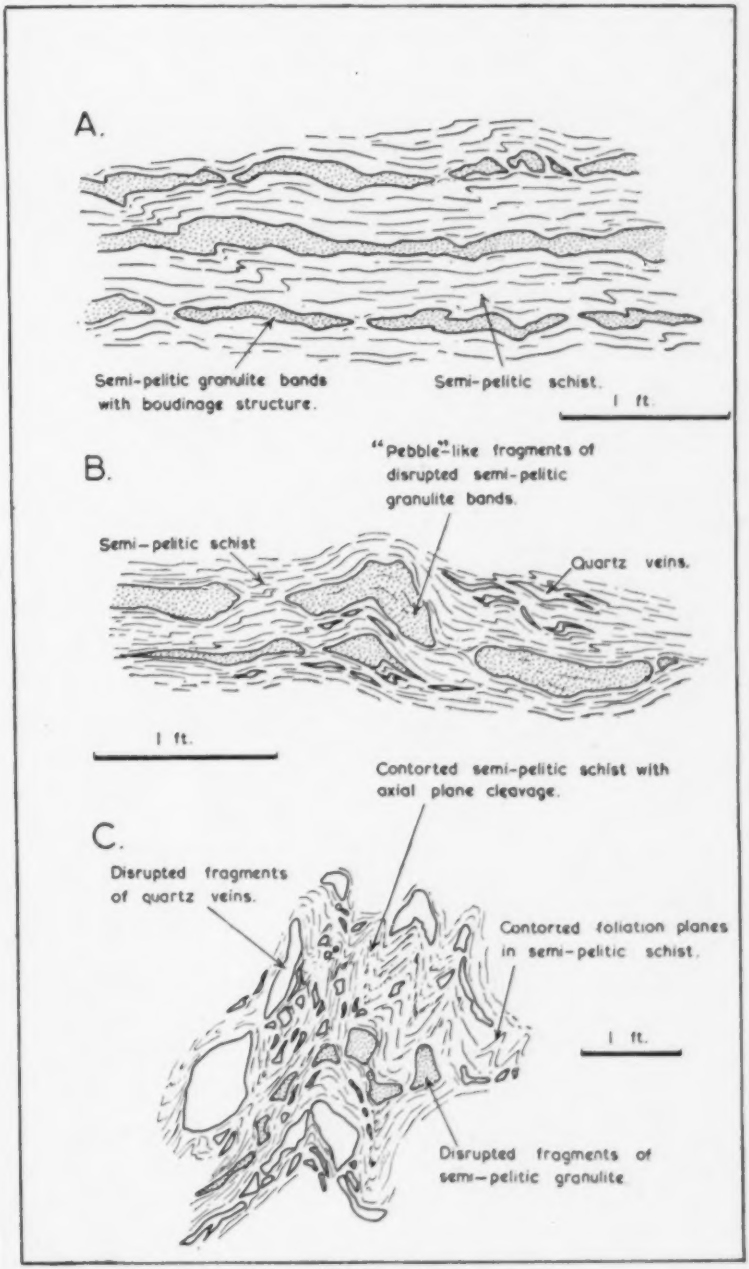
reinvestigation shows that the supposed Lewisian rocks occupy a position between the pelitic and semi-pelitic rocks to the south-east and the psammitic rocks to the north-west (see section across Text-fig. 1). The supposed Moinian basal conglomerate was recognized by Anderson along the south-east margin of the " inlier ". If the apparent succession seen in the section across Text-fig. 1 is the " right way up " then the supposed conglomerates are to be found below the " Lewisian " sheet. Although supposed conglomerates were originally only recognized in the Moine Series a re-examination of the ground has shown

that very similar structures can be found within the boundaries of the supposed inlier (localities shown in Text-fig. 1).

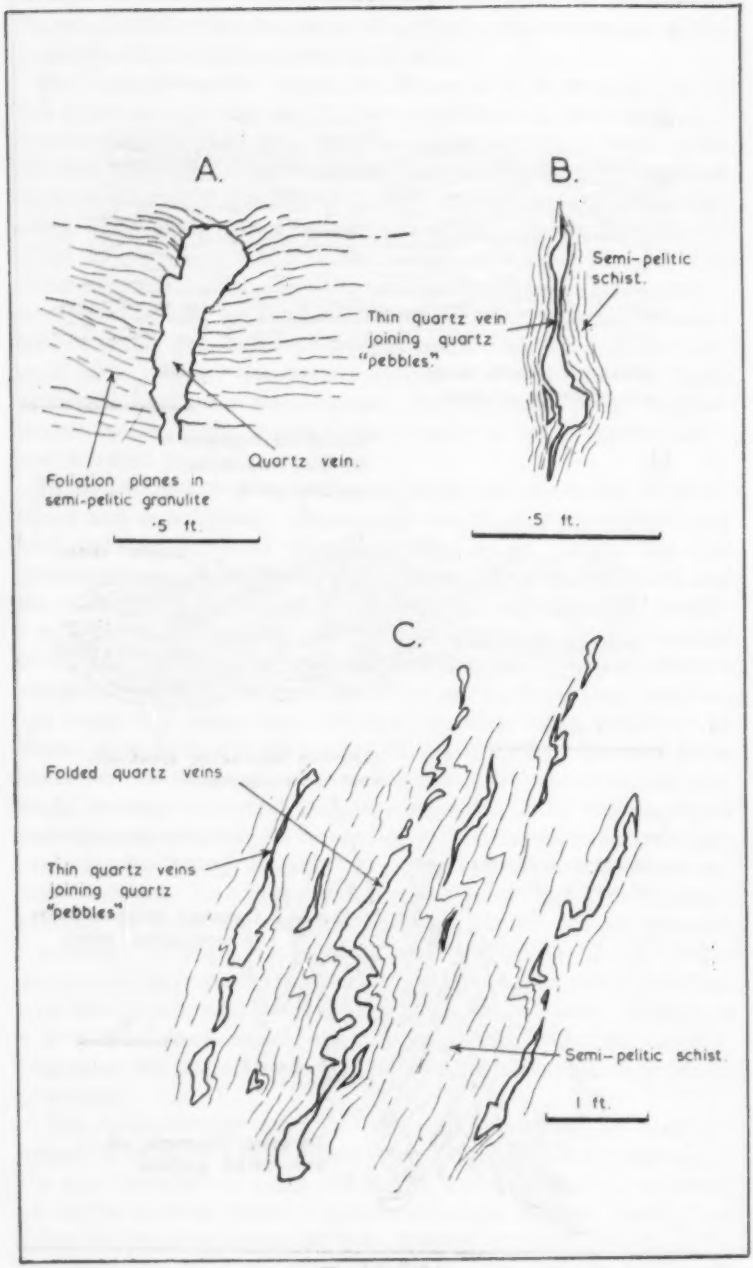
The " conglomeratic " structures always occur in areas where the rock types are made up of a banded assemblage of alternating competent and incompetent beds. Such an assemblage can be found to the east and south-east of the supposed inlier and consists of competent bands of psammitic granulite in a matrix of incompetent semi-pelitic schist. The quartz-feldspar-muscovite granulite bands are generally about 2–6 inches in thickness but occasionally reach 10 feet. The thickest of these massive psammitic bands never show "conglomeratic " structures. These structures are found wherever the thin granulite bands together with the matrix of semi-pelitic schist are contorted into small folds. When these rocks occur in an unfolded condition " conglomeratic " structures are never seen. In many places along the south-eastern margin of the " inlier " the evolution of the " conglomerate " can be traced in adjacent outcrops.

In the least disturbed rocks the competent granulite bands are gently folded and boudinaged. Occasionally the boudins are separate and form flattened lenticular sheets (Text-fig. 2, A). Where the fold movements were more intense the schistose matrix is drag folded and the psammitic granulite bands are disrupted into elongated pseudo-" pebbles " (Text-fig. 2, B). All stages of separation of the competent bands into " pebble "-like fragments can be seen. These fragments are elongated parallel to the prominent linear structures (striping, lineation, and minor fold axes), found in the surrounding rocks, which can be shown to be parallel to the axes of the major folds in this area. Some bands are unfolded and no " conglomeratic " structures can be seen, whilst strongly contorted neighbouring rocks show well-developed pseudo-conglomerates. As the semi-pelitic matrix becomes increasingly contorted the " conglomeratic " structures become very abundant and well-developed. Even in the most intensely folded rocks it is generally possible to trace the original band-like nature of the granulite " pebbles " through the schistose matrix (Text-fig. 2, C). Petrographically the disrupted fragments of psammitic granulite are identical with the undisrupted granulite bands in the Moine Series. If this were a true basal conglomerate the pebbles would be derived Lewisian fragments and might be expected to bear little resemblance to Moine granulites.

The conglomeratic quartzite fragments described by Anderson appear to be derived from quartz veins. Quartz veins are common in the most undeformed rocks and can be found parallel to, or cutting across the foliation planes in semi-pelitic rocks. Quartz " necks " are found in the more competent beds between boudins (Text-fig. 3, A). In folded and deformed rocks the quartz veins become folded and


A.
Semi-pelitic granulite bands with boudinage structure.
Semi-pelitic schist.
1 ft.
B.
"Pebble"-like fragments of disrupted semi-pelitic granulite bands.
Semi-pelitic schist
Quartz veins.
1 ft.
Contorted semi-pelitic schist with axial plane cleavage.
C.
Disrupted fragments of quartz veins.
Contorted foliation planes in semi-pelitic schist.
1 ft.
Disrupted fragments of semi-pelitic granulite

TEXT-FIG. 2.


A.
B.
Thin quartz vein joining quartz "pebbles."
Semi-pelitic schist.
Quartz vein.
Foliation planes in semi-pelitic granulite
·5 ft.
·5 ft.
C.
Folded quartz veins
Thin quartz veins joining quartz "pebbles"
Semi-pelitic schist.
1 ft.

TEXT-FIG. 3.

lenticular. They become drawn out into elongated, rod-like, foliated quartz " pebbles " (Text-fig. 3, B and C) which have some resemblance to quartzites of sedimentary origin. The disrupted fragments are frequently connected by thin quartz veinlets. The broken quartz fragments usually retain their original vein-like arrangement even in the most strongly deformed and folded rocks (Text-fig. 2, C).

In some places the " conglomerate " rock has become feldspathized, and streaks and augen of coarse-grained quartzo-feldspathic material are fairly abundant.

The supposed conglomeratic structures are not restricted to any one stratigraphical horizon. In most places where the rock types are characterized by thin competent bands in an incompetent matrix pseudo-conglomeratic structures can be found. Some of the rock originally mapped as Lewisian between Inchvuilt and Carn Mor has pseudo-conglomeratic structure. Thin hornblendic and calc-silicate bands are to be found as rod- and spindle-shaped bodies in a matrix of biotite schist. On Carn Mor and Carn na Saile Leithe it is possible to trace the trains of amphibolite and calc-silicate " pebbles " for considerable distances along the strike parallel to the nearby thicker, more competent, undisrupted hornblende and calc-silicate bands.

It can be concluded that the structures resembling a conglomerate are of tectonic origin. These structures are always best developed in highly folded rocks and appear to have been produced during a period of major folding. The axial planes and fold axes of minor folds in outcrops of the " conglomeratic " rock are parallel to those of the major fold structures which have been recognized in this area. Somewhat similar broken quartz rod structures in the Moine Series at Ben Hutig have been described by Gilbert Wilson (1953) and crushed gneisses with a deceptive resemblance to a conglomerate near Kirkton of Lochalsh have been described by Horne (in Peach and others, 1910, p. 44). Clough (in Peach and others, 1910, p. 51) discusses the origin of long quartz rods that were found in the supposed Moinian basal conglomerate at Glenelg and comments:

". . . we hesitate to say whether they represent pebbles or quartz veins."

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Carboniferous Goniatites from Blacklion, Co. Leitrim, Ireland

By Frank Hodson

Abstract

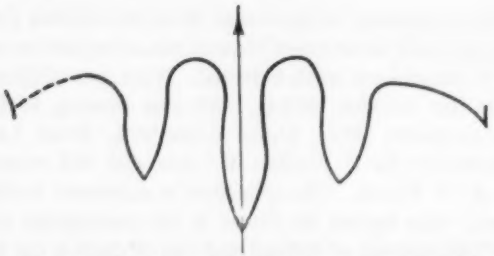
The holotype of *Brancoceras enniskillense* Foord, 1903, is shown to be a specimen of *Beyrichoceras excavatum* (Phillips), 1836, the suture line of which has been misinterpreted. It is associated with *Beyrichoceras castletonense* (Bisat), indicating the presence of the Upper B_2 subzone in the Carboniferous Limestone, of Blacklion.

A SMALL collection of goniatites from the Griffith Collection in the National Museum of Ireland was submitted to me by Miss G. Roche, to whom I am much indebted. It consists of four specimens mounted on five wooden tablets, each one bearing McCoy's label "*Goniatites excavatus* Phil., Upper Limestone, Black Lion, Enniskillen, Presented by Sir R. Griffith Bt." and with MS. notes affixed to the rear by A. H. Foord. The collection is important in that three of the specimens were figured by Foord in his monograph on the Carboniferous Cephalopoda of Ireland and one of them is the holotype of *Brancoceras enniskillense* Foord.

The holotype of *Brancoceras* (now *Imitoceras*) *enniskillense* is a fragment of a specimen the estimated dimensions of which are : diameter 42 mm. ; thickness 19 mm. ; umbilical width 8 mm. Only about a half of the two outer whorls is preserved and the nucleus has been detached, but one of the other specimens in the collection proves to be the missing nucleus of the type specimen which is described and figured by Foord (1903, p. 208, pl. 47, figs. 3a–b). Foord states (p. 209) that he referred the specimen to the genus *Brancoceras* after seeing the sutures " defined upon the hollow mould left by the removal of the innermost whorls in extracting the fossil from the rock ". However, re-examination of the specimen, and recognition that the nucleus which was removed from the " hollow mould " is in fact still available, shows that the suture line which Foord saw was really the dorsal suture of the penultimate whorl and not an impression of the ventral suture of the whorl preceding this. The suture line is figured in Text-fig. 1. It will be seen that in general character it resembles the ventral suture of *Imitoceras*, especially in the undivided central lobe which Foord took as the ventral lobe. If, however, as there can be no doubt, this lobe is the dorsal lobe, then it has the general aspect of all goniatites.

The visible suture is a dorsal suture for three reasons. (i) If it is interpreted as a ventral suture it comes nearest to either *Imitoceras* or *Gattendorfia*, but it will be seen from Text-fig. 1 that the lobe then interpreted as the ventral lobe is much deeper than the presumed lateral lobe. This would be very different from the condition in either

of these two genera and cannot be matched in any other. (ii) The umbilical width of the specimen is 19 per cent of the shell diameter. This is too wide for *Imitoceras* and too narrow for *Gattendorfia*. Schmidt (1925, p. 527) accepting Foord's species, discriminates it from other acutely ventered species of *Imitoceras* by the wide umbilicus. (iii) A plasticine squeeze or an inspection of the detached nucleus shows the suture line to be preserved as a sinuous calcitic thread lying on *top* of the shell ornament and elevated above the level of the test ; a sure indication of the true nature of the suture.



TEXT-FIG. 1.—The dorsal suture of *Beyrichoceras excavatum* (Phill.) from the holotype of " *Brancoceras enniskillense* " Foord.

We must conclude therefore that Foord's *enniskillense* is not a species of *Imitoceras*. It has been wrongly interpreted and must now be re-identified. In general shape, especially in the development of an acute venter at 33 mm. shell diameter, it invites comparison with *Sagittoceras discus* (Roemer), but such growth striae as are visible do not show a pronounced lingua. From careful examination of the specimen, I am convinced that McCoy's original identification is correct and that it is *Beyrichoceras* (*Bollandites*) *excavatum* (Phill.), possibly the form referred to by Bisat (1934, p. 287) as *Beyrichoceras* cf. *excavatum* mut. towards *micronotum*.

Two other specimens figured by Foord (1903, pl. 48, figs. 2 & 3) prove to be *Beyrichoceras* (*Bollandites*) *castletonense* (Bisat) thus dating the beds from which they came as Upper B_2.

The fourth specimen is very poor. It is a beyrichoceratid, and Foord has inscribed the tablet bearing it " not determined ".

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The Old Red Sandstone Lavas of the Western Sidlaw Hills, Perthshire

By W. T. Harry

Abstract

The Old Red Sandstone lavas of the Perthshire Sidlaws are basalts with some andesite-basalts, andesites, and rare trachyandesite. The basalts comprise chiefly olivine-bearing flows that include feldspar-phyric and aphyric varieties; olivine-free basalts with two pyroxenes are of restricted distribution.

The significance of augite textures and their relationship to augite content in the basalts is discussed.

The lava pile is apparently composed of interdigitating lenticular flows that vary from a few feet up to about 80 feet in thickness.

Unlike most other Scottish Old Red Sandstone lava suites the Sidlaw suite is fairly fresh and, like the Eastern Forfarshire lavas, it is relatively basic.

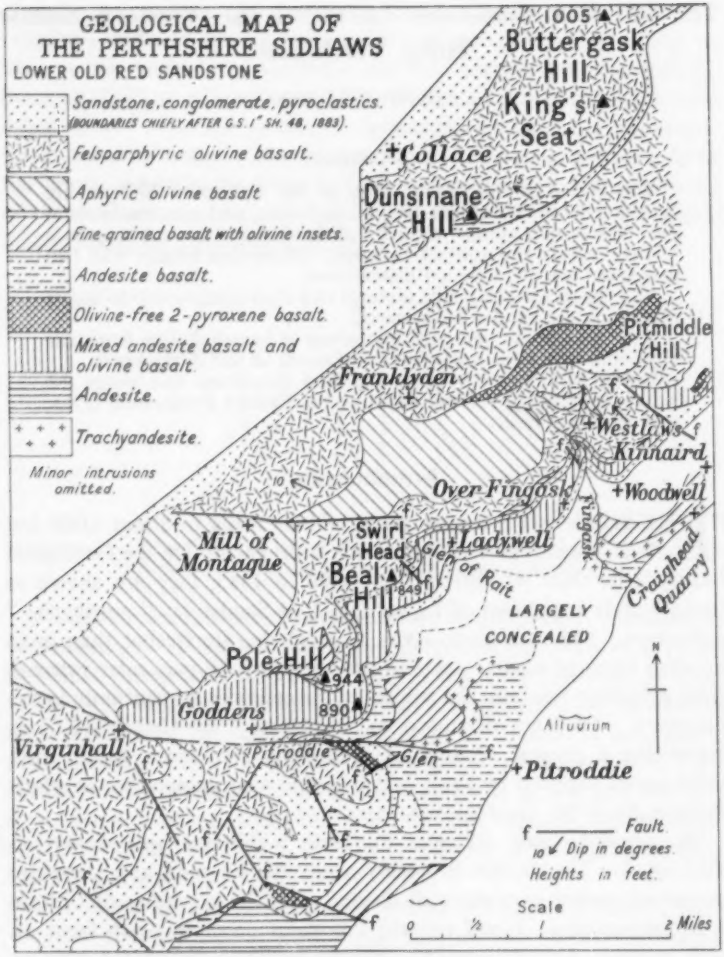
Introduction

THE Sidlaws are a narrow range of hills rising to about 1,000 feet O.D. extending north-eastwards from Perth. On the Geological Survey 1-in. sheet 48 (Perth), published in 1883, they are shown as being largely composed of Lower Old Red Sandstone " porphyrite " extrusives. Although these lavas, as a whole, are fresher than most Scottish lavas of similar age and are therefore of particular interest, their petrology has been the subject of superficial comment only in the literature. They are dismissed as " andesites " by Geikie (1897) in presenting a general account of their field occurrence based upon information supplied by Prof. James Geikie who mapped the Western Sidlaws for H.M. Geological Survey.

The present paper describes the lavas within the area shown on Text-fig. 1. The district is readily accessible by road and there are numerous quarry exposures all disused with the exception of Collace roadstone quarry. Good natural exposures occur in scarp faces on high ground. Lavas from 140 different localities distributed over an area of approximately 23 square miles of lava were sliced and about sixty days were spent in the field.

Field Occurrence

The Sidlaw lavas comprise part of the north-western limb of the Tay anticline and their estimated general dip is about ten degrees to the north-west. The structure is topographically expressed in many well-defined dip and scarp slopes. A traverse across the strike of the hills through Kinnaird village north-westwards shows an ascending succession of about 3,000 feet of Lower Old Red Sandstone rocks,



TEXT-FIG. 1.

chiefly lavas but including about 200 feet of sediments occurring at several horizons. There is no visible base to the lava pile.

The flows vary from a few feet up to roughly 80 feet in thickness but intermediate values greatly predominate. Some flows, especially those with megaphyric feldspars, are very slaggy and amygdaloidal but most are compact and display well-developed slightly curved joints. Haematite replacement veinlets are common and sandstone veins fill cracks in the tops of a few flows.

The field distribution of the various lavas is shown on the map (Text-fig. 1). Some areas depicted as consisting of one lava type only actually contain a few subordinate flows of other varieties of lava which it has been impossible to represent with clarity on the map. The distribution of the different lavas leads to the recognition of several faults, for example, the east–west fault through Pitroddie Glen along which the country south of that glen has apparently been faulted down. Supporting evidence for this fault is the common occurrence of fault breccias along the bottom of the glen and the presence of an east–west dyke following the lower reaches of the glen. It is also significant that Pitroddie Glen separates two areas of different topography, a northern area of pronounced dip and scarp slopes and a southern tract of country of lower elevation and with much less marked scarp and dip slopes.

The map also shows that several lava units thin out along the strike. This leads to consideration of the form of individual flows within the lava pile. Those few flows that can be followed across country for some distance provide evidence that the lava pile is composed of lenticular interdigitating sheets. For example, a conspicuous horizon in the succession suitable for close study is a feldspar-phyric olivine basalt resting on coarse conglomerate seen near the top of Pole Hill. Both rocks can be followed for about 2½ miles north-eastwards from Pole Hill and are well exposed in crags on the north side of a dry glacial channel at Swirlhead, Glen of Rait, where the flow is about 50 feet thick and can be seen in contact with the underlying conglomerate which is at least about 20 feet thick here. North-eastwards from this locality both rocks can be traced with certainty in abundant exposures for a mile to near Over Fingask, whilst the feature due to the flow gradually fails as the flow thins out. For about half this distance from Swirlhead the flow is visible in contact with the conglomerate at several places, but a few hundred yards beyond the last exposure of this contact andesite overlies the conglomerate and can be followed to the vicinity of Over Fingask interposed between the conglomerate and the feldspar-phyric olivine basalt. This andesite was sampled for analysis with results given in Table 1. Continuing north-eastwards from here along the strike to Fingask valley, exposures are not so frequent, but a conglomerate exposed in the river appears to be the same bed as that seen north-west of Over Fingask, although it is overlain by feldspar-phyric olivine basalts. These observations suggest that the thicker lava flows may persist for a few miles along the strike and that the individual lava flows composing the volcanic pile are arranged as interdigitating lenses.

Regarding variations in petrographical character within individual flows, little evidence has been obtained. The feldspar-phyric olivine

basalt seen in the crags on the north side of Swirlhead shows no apparent change in size and amount of feldspar insets from base to top, and other flows seem also homogeneous. Collace roadstone quarry, however, presents some evidence of slight vertical variation in composition within one flow. This opening seems cut in a single flow about 80 feet thick, although there is some disturbance in the centre of the working face, marked by abundant slickensided surfaces coated with lustrous chloritic minerals. Specimens from the top of the flow are slightly paler in colour and contain a little less olivine and pyroxene than samples near the base.

Petrography

The lavas of the Perthshire Sidlaws comprise the following rocks, stated in what is roughly estimated to be their order of abundance: olivine basalts, andesitic basalts, olivine-free basalts with two pyroxenes, andesite, trachyandesite. Fresh olivine has not been detected.

The basalts approach andesitic character. The average composition of total feldspar in each slice lies near the andesine-labradorite boundary and the colour indices of the basalts are usually much lower than 40, whilst the statistical work of Ellis (1948) indicates that this value marks a natural division between most basalts and andesites, the colour indices of the former reaching a peak at 50.

Measurements of 2V given below were made by direct measurement on the Universal Stage in sodium light.

Olivine Basalts

Hand specimens of these are generally almost black in colour and of fresh appearance when hammered. Thin-sections of such specimens show fresh feldspar and augite, but olivine is always totally altered.

Several different varieties based largely on textural criteria can be distinguished.

(*a*) *Feldspar-phyric Olivine Basalts.*—These contain feldspar insets in variable quantities from only a few individuals per slice up to about half the volume of the rock. An unusual doleritic variety occurs at a few localities notably at a place bearing 5 degrees (true) and 3,700 feet from Westlaws. This contains more dark minerals than many of the olivine basalts; augite forms plentiful subophitic plates and olivine pseudomorphs are common.

The feldspar-phyric olivine basalts comprise megaphyric varieties in which the feldspar insets are 1·5 mm. or more in length and microphyric varieties in which the insets are smaller. The two varieties occur in roughly equal quantities. In a small number of megaphyric olivine basalts the feldspar insets range from 3 mm. to 1 cm. in length but n most flows the insets are smaller. In the vast majority of micro-

phyric basalts the groundmass feldspar laths measure up to about 0·4 or 0·5 mm. in length and there is no strongly marked distinction between the two generations of feldspar; olivine is usually aphyric and augite is subophitic or granular. But in some flows, for example that at Westlaws, near Kinnaird, the groundmass feldspar is notably finer-grained and there is a sharp distinction between insets and groundmass, the former being plentiful and about 1 mm. long. Augite forms abundant tiny grains and also, occasionally, microphenocrysts. Olivine forms scattered microphenocrysts. Tiny iron ore grains are abundant and a little intersertal glass may occur. Apart from these differences the feldspar-phyric olivine basalts can be described collectively as follows.

Plagioclase insets sometimes form small glomeroporphyritic clumps that may also include a few augite insets. Feldspar insets rarely present a rounded outline. Most of them are roughly rectangular often with jagged broken edges. Cleavage fragments can now and then be seen in process of detachment from an inset and in a very few zoned insets it is seen that the insets have been broken across the zones. Microscopic fractures occasionally displace slightly the twin lamellae of insets and may be filled with alkali feldspar or green decomposition products.

Normal oscillatory continuous and discontinuous zoning is often developed, most zones being about acid labradorite although thin andesine-oligoclase rims are often present. Unzoned insets are labradorite. Both zoned and unzoned crystals may occur in the same slice. Albitization slightly affects some insets.

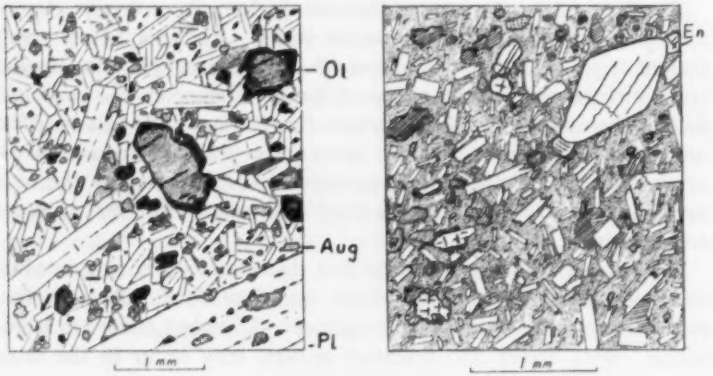
Inclusions of augite, green decomposition products and iron ore are common, the first being occasionally concentrated along certain (010) planes in the host. Not uncommonly insets are honeycombed with glassy inclusions and may then display well defined inclusion-free rims. The insets may display flow structure.

Groundmass plagioclase forms laths from about 0·1 to 0·5 mm. in length of andesine-labradorite, usually of slightly more sodic composition than the associated insets. Continuous zoning to thin oligoclase rims or, more rarely, oscillatory zoning can be seen. Albitization is sometimes visible. Fluxion may be developed.

Augite is virtually non-pleochroic, faintly brown or pinkish-brown, forming small granular or subidiomorphic crystals or else subophitic areas irrespective of whether the groundmass feldspar is fluxioned or not. The subophitic augite forms irregular often roughly lenticular patches up to about 1 mm. in length; one specimen gave $(+)\,2V = 49°$. Feldspar laths penetrating the augite areas do so with rectangular, not wedge-shaped terminations, and may be strongly fluxioned, forming the trachy-ophitic texture of Elliott (1952).

Augite grains and subidiomorphic crystals average 0·1–0·2 mm. in width and may tend to cluster. They may become moulded on to contiguous feldspar or penetrate the edges of the latter and they may be concentrated along the edges of olivine crystals. They are often accompanied by augite insets up to a few mm. in width and sometimes forming small clumps. These insets may show simple twinning and in slices of several megaphyric and microphyric basalts they gave (+) 2V = 50°–54°.

Rhombic pyroxene does not occur unaltered or in characteristic pseudomorphs, but a very few slices contain some small serpentinous areas that may represent rhombic pyroxene.



TEXT-FIG. 2.—A. Feldspar-phyric olivine basalt, Swirlhead. Analysed specimen 1 in Table 1.

B. Andesite. Analysed specimen 4 in Table 1. Enstatite insets, augite grains (heavy stipple), chlorophaeite, and serpentinous areas (ruled), andesine laths in abundant feldspathic ground charged with iron ore dust (fine stipple).

Olivine is always totally altered, most commonly to green serpentinous or chloritic matter, sometimes to iddingsite, iron ores or carbonate; iron ores and iddingsite commonly form rims and line cracks in pseudomorphs when they do not completely replace the olivine themselves. Olivine is present in only small or moderate quantities and often presents characteristic outline; bipyramidal terminations are common. Sometimes it forms insets 1–2 mm. long.

The occurrence of altered olivine in rocks otherwise fresh indicates that the alteration is due not to weathering but to processes connected with the magmatic history of the area. But unlike many olivine basalts that contain altered olivines due to regional pneumatolysis such as certain of the Mull lavas (Bailey, 1924) epidote is not developed.

Perhaps the serpentine alteration of olivine in the Sidlaw lavas took place at an early stage in the crystallization of the flows.

Accessories are iron ore in bars and grains, and tiny apatite prisms. Occasionally thin bars of iron ore in strongly fluxioned basalt can be seen set at random across the fluxion of the feldspar suggesting that the iron ore was of late crystallization, perhaps filling microscopic cracks in the rock.

Very occasionally some tiny flakes of pale brown mica may be present.

In many specimens some intersertal glassy or feldspathic residuum is present both in fluxioned and non-fluxioned rocks and in rocks with either granular or subophitic augite. Present usually in small quantities only it consists of a weakly birefringent base that may be clear, or turbid with finely-divided iron ore, and with a refractive index ranging from slightly above to slightly below 1·54 but always less than that of the associated groundmass plagioclase. Albite twinning is occasionally visible.

Small or moderate and occasionally abundant amounts of intersertal green serpentinous or chloritic matter, or chlorophaeite are generally present.

In a few slices part of the colourless intersertal matter consists of abundant tiny microspherulites.

(*b*) *Aphyric Olivine Basalt.—Plagioclase* in these rocks is often fluxioned and varies from about 0·2 to 1 mm. long in most slices presenting a seriate texture in which the predominant length of the feldspar is about 0·5 mm. Sometimes, however, the laths are all roughly the same length. Zoning is common and usually normal continuous, culminating in thin oligoclase rims, but normal oscillatory zoning may occur as also may slight albitization. The main body of the crystals is of acid labradorite to basic andesine composition.

Augite is usually subophitic and measurements of subophitic augite from several flows gave (+) 2V = 47°–49°. It otherwise occurs with the same general appearance and textural relationships as the augite in the feldspar-phyric olivine basalts.

Olivine occurs as in the feldspar-phyric olivine basalts except that it may become very scarce and, in a few slices, almost absent as in the analysed specimen 3 (Table 1).

Accessories and intersertal matter occur as in the feldspar-phyric olivine basalts. One slice contained small fine-grained segregations of granular alkali feldspar and quartz.

(*c*) *Fine-grained Basalts with Olivine Insets.*—These are characterized by moderate numbers of conspicuous olivine insets up to 1 mm. long and tending to idiomorphism set in a ground of small plagioclase

laths averaging from about 0·1 up to, in a few slices, about 0·4 mm. long and often fluxioned. Occasional small plagioclase microphenocrysts sometimes occur. Albitization may be extensive and rocks of mugearitic aspect may then be formed. In unaltered specimens the feldspar is basic andesine-labradorite.

Augite forms numerous small grains. The olivine is totally altered, usually to green serpentinous matter, with iron ore rims.

Interstitial alkaline residuum with R.I. slightly below 1·54 is often present and iron ore grains are accessory.

(*d*) *Olivine-free Basalts with two Pyroxenes.*—A chemical analysis of one of this small group of basalts is given in Table 1.

Plagioclase in these rocks commonly assumes microphyric texture and albitization is absent. Slight normal zoning has been noted. The composition is about acid labradorite.

Pyroxene.—Orthopyroxene generally forms numerous aphyric pseudomorphs in green serpentinous matter. Augite in small quantities occurs as fresh grains, insets or subophitic areas as in the olivine basalts.

There are small amounts of intersertal glassy residuum turbid with iron ore. Apatite and iron ore are accessory.

Andesitic Basalts

These rocks are usually lilac, pinkish- or reddish-coloured in hand-specimen. They contain much less pyroxene than the basalts. *Plagioclase* is andesine or, sometimes, acid labradorite, frequently in two generations and highly albitized, the lime released during albitization effecting considerable carbonate replacement in the rock. *Augite* forms tiny scanty pseudomorphs in the groundmass. *Rhombic pyroxene* occurs in a few slices as scattered porphyritic pseudomorphs. *Olivine* is always altered, usually to pseudomorphs in carbonate or silica with iron ore rims. It forms moderate numbers of small aphyric crystals or insets about 1 mm. long often with the " resorbed " outline customarily ascribed to corrosion.

A glassy or indeterminate fine-grained feldspathic residuum is usually present and is often very abundant. It may be turbid with iron ore. Secondary iron ores are usually plentiful.

A few flows, seen in the northern lowest slopes of Pitroddie Glen a little over half a mile east of Goddens seem intermediate between the basalts and andesites and are shown on Text-fig. 1 as andesite-basalt, but differ slightly from the rocks just described. They are either olivine-free or contain small, very sparse olivine pseudomorphs, usually in iron ore. Augite occurs in moderate amounts, sometimes as insets, and rhombic pyroxene forms scattered insets usually as bastite pseudomorphs, but it is sometimes unaltered and then shows the

TABLE 1.—CHEMICAL ANALYSES OF OLD RED SANDSTONE LAVAS, SIDLAW HILLS AND FIFE

	1	2	3	4	5	6	7
SiO_2	50·62	48·80	51·46	53·35	54·01	56·45	49·78
TiO_2	1·48	1·77	1·47	1·16	1·38	0·92	1·48
Al_2O_3	16·58	18·03	17·93	15·22	15·1–*	16·22	16·84
Fe_2O_3	3·77	3·96	7·20	2·14	3·98	2·81	2·28
FeO	3·93	4·28	2·01	4·56	3·39	3·84	5·60
MnO	0·22	0·23	0·12	0·43	0·30	traces	0·13
MgO	6·87	4·74	4·13	7·42	3·34	5·68	7·62
CaO	8·44	8·02	6·94	6·81	6·37	5·34	7·68
Na_2O	2·78	3·26	3·65	2·92	5·58	4·32	3·18
K_2O	1·12	0·82	1·36	0·76	2·61	1·90	0·95
H_2O+	1·64	1·72	1·34	1·98	1·18	0·90	2·42
H_2O-	2·16	3·88	1·77	3·27	1·77	1·48	1·98
CO_2	nil	nil	nil	traces	0·05	nil	nil
P_2O_5	0·34	0·26	0·34	0·21	0·67	0·28	0·26
	99·95	99·77	99·72	100·23	99·73	100·14	100·20

(Analyst: W. H. Herdsman, except No. 5, which is by R. Phillips.)

* By Shapiro and Brannock's direct colorimetric method.

Norms

	1	2	3	4	5	6	7
qz	4·02	3·42	5·58	7·20	—	4·62	—
or	6·67	5·00	8·34	4·45	15·57	11·12	5·56
ab	23·58	27·77	30·92	24·63	45·59	36·68	26·72
an	29·47	31·69	28·08	26·13	8·34	19·18	28·91
ne	—	—	—	—	0·85	—	—
$CaSiO_3$	4·41	2·55	1·86	2·78	7·66	2·09	3·36
$MgSiO_3$	17·1	11·8	10·3	18·5	6·0	14·2	17·4
$FeSiO_3$	1·85	2·12	—	5·54	0·79	3·17	5·54
Mg_2SiO_4	—	—	—	—	1·60	—	1·12
Fe_2SiO_4	—	—	—	—	0·20	—	0·41
mt	5·57	5·80	2·32	3·02	5·80	4·18	3·25
il	2·89	3·34	2·89	2·28	2·74	1·67	2·74
hm	—	—	5·60	—	—	—	—
ap	0·67	0·67	0·67	0·34	1·68	0·67	0·34
cc	—	—	—	—	0·1	—	—

1. Feldspar-phyric olivine basalt (megaphyric variety), 200 feet south of road at Swirlhead, Glen of Rait, and 1,500 feet west of Ladywell.
2. Olivine-free two-pyroxene basalt, 5,400 feet north-west of summit of Guardswell Hill, Kinnaird, and 20 degrees (true) and 4,500 feet from Westlaws.
3. Aphyric basalt. East side of quarry 700 feet west of Mill of Montague, about 1½ miles west of Swirlhead.
4. Andesite (basic variety). 1,400 feet and bearing 300 degrees (true) from Over Fingask.
5. Trachyandesite. Craighead Quarry, north side of road, 2,300 feet south-west of crossroads at Kinnaird.
6. Andesite. Wormit, Fife, first exposures at western end of beach, Wormit Bay.
7. Olivine basalt, first inlet on shore west of Woodhaven pier, near Wormit, Fife.

properties of enstatite. Andesine-labradorite forms insets up to about 2 mm. long and small groundmass laths.

Andesites

The analysed specimen contains microphyric feldspars and lies at the basic end of the group, but the other flows in this group are megaphyric and apparently more acid; they are described as follows.

Andesine-acid labradorite insets a few mm. long are abundant. They show features similar to those of the feldspar insets of the olivine basalts. The groundmass includes small andesine laths and microliths less than 0·1 mm. long in some slices that may or may not be fluxioned. Augite occurs as scanty tiny pseudomorphs in carbonate and iron ore. Orthopyroxene forms scattered insets up to 1 mm. long usually replaced by bastite and with characteristic outline. A fine-grained feldspathic residuum often coloured by opaque dust and with R.I. less than 1·54 is abundant.

Accessories that may occur are apatite needles, iron ore, and a brown mica.

Trachyandesite

In hand-specimen these rocks are fine-grained and of medium-grey colour when fresh being notably paler than the unweathered basalts. A chemical analysis of one specimen (Table 1) clearly shows its trachyandesite nature when plotted on the diagram of Walker (1952).

Thin-sections are composed chiefly of small fluxioned laths of sodic plagioclase with intersertal alkaline residuum; there are a few small augites and accessory apatite. Secondary iron ore is common.

The Significance of Augite Textures

In basic igneous rocks from various regions Tomkeieff (1945, p. 74) finds a relation between pyroxene texture and mineral and chemical composition. Idiomorphic pyroxene usually occurs in rocks rich in alkali feldspar or in rocks where the pyroxene ratio

$$\left(\frac{\text{pyroxene}}{\text{pyroxene} + \text{feldspar}} \times 100\right)$$

of *the groundmass* exceeds a certain value that depends upon the composition of the feldspar, being high with alkali feldspar and low with lime feldspar. In rocks with similar feldspars the pyroxene-rich types almost invariably contain idiomorphic pyroxene and the feldspar-rich types usually contain ophitic pyroxene.

Similar relationships are displayed by the Sidlaw lavas. Thirty slices of feldspar-phyric and aphyric basalts, the former predominating, were selected for modal analysis by Shand stage. Roughly half of them contained subophitic augite. The following results were obtained

expressed as volume percentages of augite in the whole slice, *not* groundmass alone:—

	Subophitic Augite.	*Intergranular Augite.*
	%	%
Feldspar-phyric basalt:		
Range . .	5–10	10–22
Average . .	6	15
Aphyric basalt:		
Range . .	6–8	8–18
Average . .	7·5	14

These values indicate that in the Sidlaw basalts augite is more plentiful in the intergranular varieties than in the subophitic rocks.

Considering all the slices of Sidlaw basalts feldspar-phyric basalts are more commonly intergranular than subophitic whilst the aphyric basalts are usually subophitic. This suggests that the difference in augite content shown by subophitic and intergranular Sidlaw basalts would be even more marked than in the measurements just quoted if, in feldspar-phyric lavas, the proportion of augite in the groundmass only were to be considered (Tomkeieff's pyroxene ratio).

As remarked by Tomkeieff (1945, p. 74) these augite relationships have a foundation in the order of crystallization of minerals. In all subophitic Sidlaw basalts feldspar laths penetrating augite areas do so with rectangular terminations; they do not wedge out into the augite. Many subophitic Sidlaw lavas bear indubitable evidence that the augite areas crystallized after the groundmass feldspar laths, for the areas fill interstices between fluxioned feldspars and sometimes completely surround feldspar laths aligned parallel with the general fluxion of the slice. Apart from their fluxion these slices are indistinguishable from slices of other subophitic Sidlaw basalts in which the late origin of augite is not so apparent because of the absence of fluxioned feldspars. It is concluded that augite in all subophitic Sidlaw basalts crystallized at a late stage after the groundmass feldspar and was thus compelled to occupy the interstices between those laths.

On the other hand the separation of intergranular augite overlapped the period of separation of feldspar. In the intergranular basalts augite inclusions in feldspar are not uncommon and groundmass augite may project into the sides of feldspar insets. Augite insets of obviously early crystallization are often present and vary in size down to nearly groundmass dimensions so that the period of their separation was closely followed by that of the groundmass augite. But, as may be expected, there is a notable time gap between the separation of augite insets and subophitic augite in the Sidlaw basalts,

for such insets have not been detected in the subophitic basalts. This gap appears to be reflected in the chemical compositions of the two augites. It may be recalled that augite insets in Sidlaw basalts gave (+) 2V = 50°–54° by direct measurement on the Universal Stage whilst the same method gave (+) 2V = 47°–49° for augite in subophitic basalts. The difference suggests that the insets are richer in lime than the subophitic augites, a suggestion which on general grounds from known pyroxene trends of crystallization in basaltic magma, agrees with the textural evidence of augite crystallization just discussed.

Comparison with Other Areas

A brief summary of the rather scanty literature on Scottish Old Red Sandstone lavas is provided by Robson (1948) in discussing the Eastern Forfarshire suite which, according to that author, approaches the basic end of the Scottish Old Red lavas considered as a whole and embraces a smaller range of types than many Scottish Old Red lava suites. The same remarks apply to the Sidlaw lavas, but insufficient information from elsewhere is at present available for detailed comparisons. The following comments should be made, however, on other areas in the Midland Valley of Scotland, a broad general account of which is given by MacGregor and MacGregor (1948).

From Robson's (1948) description and from slices kindly lent by Dr. Robson to the writer, it is apparent that the Sidlaw lava suite is similar to that of Eastern Forfarshire. In Eastern Forfarshire the dominant type of olivine basalt, the Usan type, includes rocks comparable with all the varieties of olivine basalt in the Perthshire Sidlaws except perhaps the rare doleritic variety of feldspar-phyric olivine basalt. Some of Robson's andesite basalts resemble the andesite basalts of the Sidlaws and certain of the present writer's olivine-poor aphyric basalts. Robson's Fotheringham type basalt is like the writer's olivine-free two-pyroxene basalt and some of the Forfarshire andesites match the Sidlaw andesites in thin-section.

On the other hand, there seems to be no large development in East Forfarshire of olivine basalt with megaphyric feldspars comparable with that in the Sidlaws and trachyandesite is absent. The basic Guthrie type basalt of Eastern Forfarshire has not been detected in the Perthshire Sidlaws.

In Kincardineshire the Lower Old Red Sandstone lavas include olivine basalts, basalts, hypersthene and augite andesites, hornblende andesite and dacite according to Campbell (1913). Rocks like the last two are absent in the Sidlaws.

The south-western extension of the Sidlaw lava belt has been described by Davidson (1932) who finds that the Lower Old Red

Sandstone lavas of Moncreiffe Hill south and south-east of Perth are olivine-enstatite-basalts.

The hypersthene-augite-andesite lavas described by Harris (1928) from the Dundee district have unfortunately not been chemically analysed, but they include specimens that, in thin-section, resemble the basic andesite (No. 4 in Table 1).

Turning to the country south of the Firth of Tay, the south-eastern limb of the Tay anticline is exposed in East Fife where the Lower Old Red Sandstone lavas according to Geikie (1902) are chiefly augite andesites, although rhombic pyroxene is also often present and olivine is not infrequent when the lavas " occasionally approach so close to the basalts that they might be called by that name " (Geikie, 1902, p. 48). These lavas are best seen in the excellent section along the south shore of the Firth of Tay between Balmerino and Tayport, Fife. From the writer's field experience they are, on the whole, more amygdaloidal and altered than the Sidlaw lavas and brecciation and sandstone veining are much more extensively developed. From Geikie's (1902) description of this section the compositional range of the lavas would appear to be much greater than that of the Sidlaw flows, for a pink felsitic rock seen at Peasehill Point, near Wormit, is there described as a dacite lava. This felsitic rock, however, is an intrusion. A large irregular mass of breccia several yards wide and containing many angular fragments of similar pink felsite can be seen near the eastern margin of the intrusion on the beach at low tide. At several places this breccia is penetrated by the felsite which also seems responsible for a thin pink acid vein intruding country rock at its western contact.

The field evidence, together with the well-known association of acid magna with explosive action, suggests that Peasehill Point is the remnant of a vent intrusion.

The two lavas from this shore section which have been taken for chemical analysis (Nos. 6 and 7, Table 1) to compare with the Sidlaw flows therefore probably lie at opposite poles of the compositional range of flows in the Fife shore section and demonstrate the general similarity between the Fife and Sidlaw lava successions.

The Lower Old Red Sandstone lavas of the Pentlands range from olivine basalt to rhyolite and are often highly altered (Flett, 1910). The olivine basalts are abundant and include many rocks similar to the feldspar-phyric olivine basalts of the Sidlaws.

Crossing finally to the western part of the Midland Valley of Scotland the Lower Old Red Sandstone lavas of Ayrshire are feldspar-phyric olivine basalts and andesites (MacGregor, 1930). The olivine basalts comprise two groups. One is characterized by abundant interstitial alkaline residuum whilst augite insets are absent and groundmass

augite is sparse. The other group contains abundant fresh granular groundmass augite, sporadic augite insets may occur, and interstitial residuum is meagre or absent. The great majority of the sliced lavas belong to the first group. The Ayrshire lavas seem therefore to include rocks similar to many of the Sidlaw lavas. From present knowledge it is difficult to draw fine distinctions between the two lava suites considered as units but it might tentatively be suggested that the Ayrshire suite as a whole is slightly less basic than the Sidlaw sequence.

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Dr. J. E. Richey kindly read the manuscript. The writer also wishes to thank Dr. D. A. Robson for the loan of thin-sections of the Eastern Forfarshire Old Red Sandstone lavas, and for discussion helpful in making detailed comparison between those lavas and the Sidlaw volcanic suite.

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The Stratigraphy and Folding of some Metamorphosed Moine Sediments around the Carn Chuinneag and Inchbae granitic gneisses.

By R. I. HARKER

ABSTRACT

By studying the current bedding in the hornfelsed rocks surrounding the ortho-gneisses of the Carn Chuinneag and Inchbae masses it has been possible to obtain some indication of the stratigraphic order and the nature of the folding of this part of the Moine series.

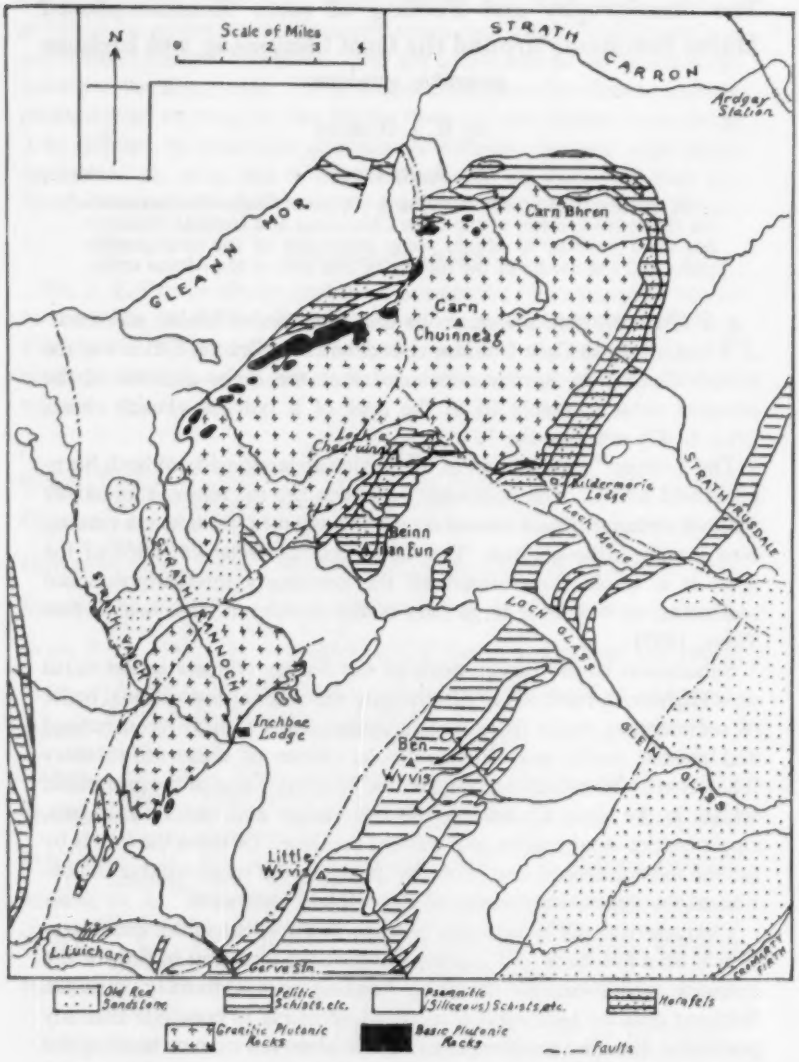
AFTER mapping the outcrops and dips of the Moine series surrounding the Carn Chuinneag-Inchbae complex the Officers of the British Geological Survey concluded that the ortho-gneisses of the complex most probably lie in the core of a syncline (Peach *et al.*, 1912, p. 47), see Text-fig. 1.

The " upper " pelitic band of the Moine series consists of both hornfelses and schists. The hornfelses now seen are the relics of an earlier thermal metamorphism caused by the intrusion of the igneous masses, now largely ortho-gneisses. The later regional metamorphism of the area as a whole transformed all the previously unmetamorphosed sediments, as well as a large part of the hornfelses, into schists (see Tilley, 1935).

Subsequent to the earlier work of the Survey Officers in the north west Highlands, methods of determining the original depositional order of sedimentary strata from certain macro-features have been refined and proved useful and fairly reliable. Some of these sedimentary features are well preserved in the pelitic hornfelses and in the psammitic schists in the Carn Chuinneag-Inchbae region and include rain pits, ripple marks, mud cracks, and current bedding. Of these the last is by far the most common and probably provides the most reliable indication of the depositional order of the original sediments.

Characteristically the current bedding in the rocks under consideration is on a fine scale and it is evident that the direction of flow of the currents which caused the false bedding was extremely variable. Without detailed plotting it is usually impossible to conclude that any particular direction predominated. In all observed current bedding the direction of younging was always the same as the direction of dip of the bedding planes, except in certain cases when the dip was greater than about 75°.

The folding in the pelitic schists is complex and frequently isoclinal. In the hornfelses folding also occurs but the folds are of greater wave length and not isoclinal. It is probable that some of this folding belongs to a period predating the final major regional metamorphism



TEXT-FIG. 1.—The granitic gneisses and rocks of the Moine Series in the Carn Chuinneag–Inchbae region (from Fig. 9, Brit. Reg. Geol. Scotland: The Northern Highlands, Geol. Surv. and Mus., 1948, by permission of the Director).

and that it occurred during or before the intrusion of the igneous masses.

In general, the schistosity in the country rocks strikes north-east

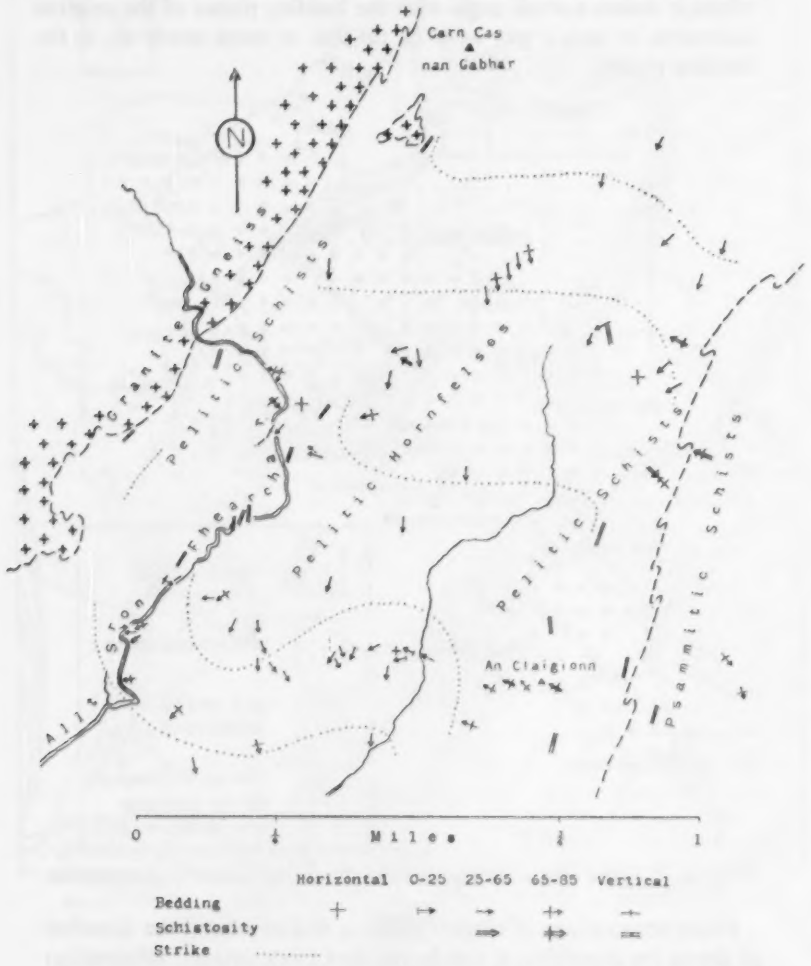
south-west in the north-east and swings round to north south in the south-west of the Carn Chuinneag–Inchbae region. The dip is predominantly to the south-east and east. There are many exceptions to this general rule and the plane of schistosity is frequently refracted, where it makes a small angle with the bedding planes of the original sediments, in such a way as to lie parallel, or more nearly so, to the bedding planes.

TEXT-FIG. 2.—The area shown in Text-fig. 1 with the author's observations.

From observations of current bedding and by noting the direction of dip in the hornfelses it was hoped that more detailed information could be obtained not only on the stratigraphy and folding in the hornfelses themselves but also on the general structure of the Carn Chuinneag–Inchbae massif as a whole. All the data so far obtained has been summarized by means of the map in Text-fig. 2.

Those outcrops which lie between Carn Cas nan Gabhar and An Claigionn were studied in some detail because they provide a key to

the general pattern of folding seen elsewhere as well as clearing up certain local problems. In the centre of the pelitic band in this region, where the hornfelses are best preserved, the rocks dip towards the south-west but on either side of this hornfelsed core, where the pelitic



TEXT-FIG. 3.—Part of the area to the east of the Carn Chuinneag Mass showing the fold pattern.

rocks are more schistose, the strike is again north-east south-west and thus parallel to the general strike of the bedding, schistosity, and foliation of the region as a whole. The map, Text-fig. 3, shows how this change is effected. It can be seen that as the strike changes direction

the angle of dip changes in amount, being nearly vertical in the schists at the sides of the band but dipping gently to the south-west in many places in the central zone. In several localities the beds in this zone are in fact horizontal.

The " S " bend which is so well displayed in the strike of these pelitic rocks is very similar to that seen in the rocks between Loch a' Chaoruinn and Beinn nan Eun which are believed to represent a continuation of the same pelitic series. On Sgor a' Chaoruinn the beds young towards the west. In this region the " S " bend of the strike is evident not so much from a general abundance of outcrops as from the outcrops of the almost unique band of " chiastolite " hornfels whose petrology has recently been discussed in connection with the poly-metamorphism of the area (Harker, 1954). Current bedding on Beinn nan Eun indicates that the series is younging towards the north-east whilst the " S " bend, though less pronounced, is still evident to some extent from a second outcrop of " chiastolite " hornfels. Evidently Loch Magharaidh lies in the core of a syncline between Sgor a' Charuinn and Beinn nan Eun.

Between Loch a' Chaoruinn and the granitic gneiss contact the metamorphosed sediments young consistently towards the granitic gneiss to the north. It would appear therefore that Loch a' Chaoruinn lies approximately in the core of an anticline.

Every observation of current bedding along the south-eastern side of the Carn Chuinneag and Inchbae masses has indicated that the country rocks at the contact young towards the granitic gneisses.

On the north-west side of the Carn Chuinneag and Inchbae masses current bedding close to the contact is not well displayed and outcrops are poor. On Meall nan Sac, however, there is little doubt that the sedimentary series youngs towards the north-east, and so away from the granitic gneiss of the Inchbae mass. This suggests that the Inchbae mass may be lower stratigraphically than the psammitic schists between the Inchbae and Carn Chuinneag masses.

The direction of younging of the beds along the contact of the granitic gneiss between Salachie and Carn nan Aighean is as yet uncertain. The rocks strike consistently parallel to the contact but fold axes parallel to this direction are also common. South-west of Beinn Tharsuinn some current bedding occurs very close to the contact. The bottom and top sets, however, are not easily distinguished from one another but it is the opinion of the writer that the beds here young away from the contact. On the Diebidale Ridge the beds young towards the south. Here, however, the examples are far removed from the granitic gneiss contact and it is unknown how many reversals the sediments undergo before the contact is encountered.

On the north side of the Carn Chuinneag mass, on the eastern slopes

of Carn Bhren, current bedding is very well developed and the bulk of the beds within a few feet of the contact young away from it towards the north. Some folding about east-west axes does occur which complicates the relationship as does a certain discordance of the granitic gneiss which is well seen around an apophysis.

It appears therefore that whereas there is good evidence from current bedding to support the original ideas of the Survey Officers concerning the stratigraphic order of the sediments of the Moine series immediately to the south-east of the Carn Chuinneag mass there is no such supporting evidence on the north-west side. It is to be noted that certain types of hornfelses and schists found in the pelitic rocks on the south-east side are not seen in the pelitic rocks on the north-west side, and vice versa. This however, may be due to a paucity of exposures, original horizontal lithological variations or somewhat different states of metamorphism, and cannot be used as evidence for a different age of the pelitic rocks in the two regions.

However, though the evidence from current bedding is far from conclusive, taken as a whole it suggests that along the north-west side the sediments young away from the contact. This, of course, would mean that the ortho-gneisses do not lie in the core of a syncline and that the pelitic rocks on the north-west side are somewhat younger than those on the south-east side.

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The author would like to acknowledge the helpful discussions which he was fortunate enough to have with Professor C. E. Tilley during the course of this work.

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The Occurrence of Chloritoid in the Hecla Hoek Formation of Prince Charles Foreland, Spitsbergen.

By D. J. Atkinson

(PLATE IV)

Abstract

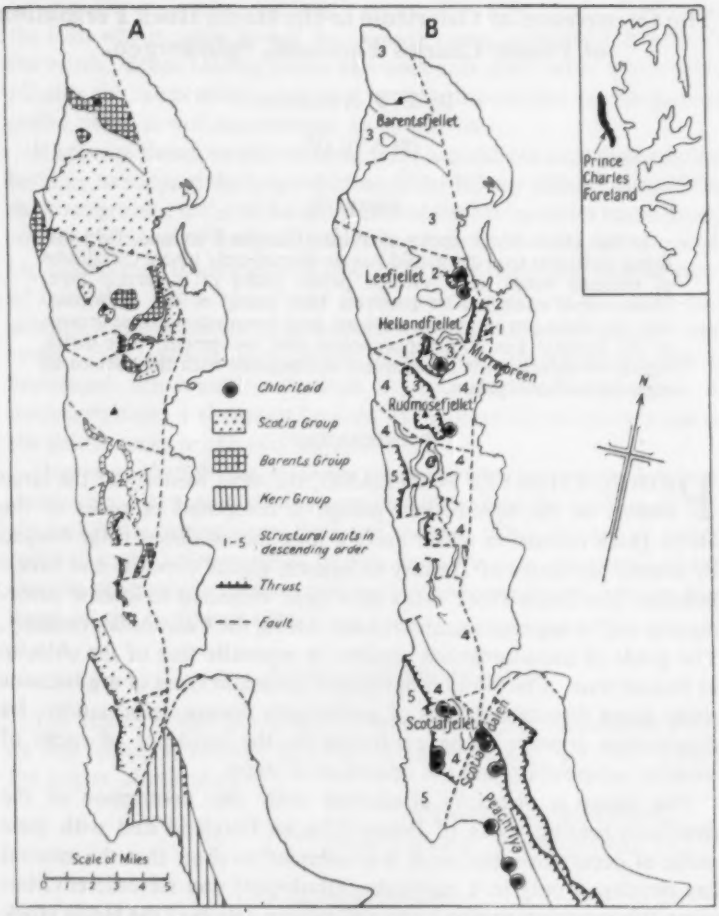
In the Hecla Hoek rocks of Prince Charles Foreland, field evidence indicates that chloritoid has developed only where conditions of extreme stress have affected pelitic rocks of a certain type. Microscopic examination confirms that many of the chloritoid-bearing rocks are extremely strained, and demonstrates that growth of the mineral was contemporaneous with movement. The distribution of chloritoid is in complete discordance with the pattern of regional metamorphism.

Introduction

PRINCE CHARLES FORELAND, the most westerly of the large islands of the Spitsbergen group, is composed of rocks of the Hecla Hoek formation which make a long mountainous ridge fringed by coastal platforms of Tertiary sediments, glacial deposits and raised beaches. The Hecla Hoek rocks have been subjected to intense deformation and to regional metamorphism during the Caledonian orogeny. The grade of metamorphism attained is generally that of the chlorite or biotite zone. Chloritoid is developed in certain types of argillaceous rocks along thrusts and belts of particularly intense deformation. Its distribution appears to be controlled by the incidence of rocks of suitable composition and the operation of stress.

This paper is primarily concerned with the description of the chloritoid-bearing rocks of Prince Charles Foreland and with their mode of occurrence, but since it is intended to show that the mineral has developed only in a particular lithological and tectonic environment, it is necessary to give some preliminary details of the Hecla Hoek rocks. The field-work on which this information is based was completed by the writer during three expeditions to Spitsbergen between 1950 and 1953, brief accounts of which have been published in the Polar Record (Atkinson 1952, 1955). The general results of the work are to be published elsewhere. For earlier accounts of the geology of Prince Charles Foreland the reader is referred to papers by Craig (1916) and by Tyrrell, who also recorded the presence of ottrelite in a boulder on the island (1924, p. 460).

The writer's re-investigation indicates that the Hecla Hoek rocks, which show strong recumbent folding, were driven westward over one another along a series of low-angle thrusts to form a pile of complex thrust sheets. Five such structural units have been recognized in the



TEXT-FIG. 1.—A. Sketch-map showing the distribution of the Barents, Scotia, and Kerr Groups in the northern part of Prince Charles Foreland.

B. Sketch-map showing the distribution of the main structural units and the localities at which chloritoid has been found.

region north of Scotiadalen and their distribution is shown in Text-fig. 1b, where they are numbered from above downwards. In general, higher units apppear in the north and east, and lower units emerge towards the south-west. The very high relief gives to the boundary thrusts an irregular outcrop which is still further complicated by later faulting. Isolated " outliers " of the higher thrust sheets can be seen on some of the mountains; Unit 3, for example, extends southward

over Unit 4 in a series of klippen, the largest of which forms the summit of Rudmosefjellet (Text-fig. 1).

In the sediments involved in the thrust sheets north of Scotiadalen a succession of four lithological divisions has been recognized. They are, from oldest to youngest, the Fuglehuk, Barents, Conqueror, and Scotia groups; two other divisions have been distinguished, but structural complications prevent their being connected to the main succession. Chloritoid occurs only in the Barents and Scotia groups: Text-fig. 1a shows the distribution of these groups.

To the south of Scotiadalen a number of lithological divisions have been recognized but their relations are complex. The only one which need be mentioned is the Kerr group (Text-fig. 1a) which underlies the raised beaches of the west coast south of Scotiadalen. This group occurs at a high structural level and over part of its outcrop rests upon a thrust.

The Occurrence of Chloritoid

Chloritoid is developed only in certain rocks of the Barents, Scotia, and Kerr groups. Although the Barents group is made up of a variety of argillaceous types, while the Scotia group consists predominantly of black slates and the Kerr group includes black slates, dark silts and quartzites, and pale phyllites, chloritoid appears only in grey or green pelitic varieties which form subordinate types in each group. Moreover the mineral is only found where these rocks of suitable composition are affected by particularly intense movement.

The *Barents Group* may be taken as the first example. On Barentsfjellet, at the north end of the island, beds of apparently suitable composition occur but they are not affected by violent localized movements. They contain no chloritoid. To the east of Leefjellet and Hellandfjellet rocks of the Barents group in Unit 3 are over-ridden by Units 1 and 2 along easterly dipping thrusts (Text-fig. 1). Below the lower thrust chloritoid develops strongly—not throughout, but only in green pelitic rocks. The grade of regional metamorphism is here exceedingly low: a short distance from the thrust argillaceous rocks have the form of poorly cleaved slates. The chloritoid appears as stubby laths, over 1 mm. in length and 0·4 mm. across, forming up to 40 per cent of the rock.

At the head of Murraybreen (Text-fig. 1), rocks of the Barents group again lie a short distance below the overthrust base of Units 1 and 2, which can be seen resting on Unit 3 in a faulted block south of Hellandfjellet. The group is here very much attenuated, being reduced from its normal thickness of more than 2,000 feet to a mere 300 feet. Chloritoid is abundantly developed in the argillaceous rocks.

The Barents group outcrops in Unit 4 further south, but the green

pelitic varieties generally seem to be sheared out or lost by facies change. Below the overthrust base of the klippe of Unit 3 that forms the summit of Rudmosefjellet, there occurs a zone of intense movement which contains lenses of rocks of the Barents group. This zone extends over the summit of the peak east of Rudmosefjellet, and here (Text-fig. 1b) a specimen showing 0·5 mm. laths of chloritoid was collected.

Chloritoid occurs in the *Scotia group* at a number of localities around Scotiafjellet, to the north of Scotiadalen. In this region the group forms part of the inverted limb of a recumbent anticline, the principal structure of Unit 4, which is thrust over un-inverted rocks of the underlying Unit 5. Chloritoid is developed at the thrust junction of the two units on a ridge some two miles south of Scotiafjellet (Text-fig. 1b), and also on Scotiafjellet itself along a series of minor slides which developed within the Scotia group during the advance of Unit 4. These localities provide further examples of the formation of chloritoid in rocks showing an extremely low grade of metamorphism ; outside the thrust zones the rocks are no more than fine-grained slates.

The lithological sub-divisions of the Scotia group have been mapped in detail in the region of Scotiafjellet, and three main parts have been distinguished. The lowest part consists of black slates with thin limestones, the middle part of black slates with a central band of grey slates, and the highest part of black slates with limestones. Chloritoid has been found only in the grey slates of the middle part of the succession and is confined to places where movement was obviously intense.

To the south of Scotiadalen chloritoid is found only in the *Kerr group*. The mineral occurs in a belt along the eastern margin of the outcrop of the group where the rocks rest with a thrust junction on a lower structural unit. A tract of vertical chloritoid-bearing rocks is seen also on the coast west of Peachflya. These rocks show considerable quartz-veining and buckling, but the presence of the sea immediately to the west makes it impossible to determine whether they lie on a definite line of thrusting.

Petrography

Chloritoid has substantially the same appearance in all the specimens from Prince Charles Foreland that have been examined. It forms conspicuous dark specks in hand specimen. In thin section it is pale greenish-grey and slightly pleochroic. There is often a rather cloudy central zone. The basal cleavage is well developed and a parting almost at right angles to it is often visible. The mineral stands out with strong relief from the ground-mass of quartz and micas.

Chloritoid-bearing rocks from the Barents group show stubby laths

of chloritoid set in a matrix of quartz and muscovite or sericite (Plate IV, A). The minerals of the matrix often show signs of extreme deformation, but the chloritoid is not cataclastically deformed. The quartz grains are frequently drawn out into greatly attenuated streaks and are granulated or very strongly strained. Small-scale isoclinal crumpling of the foliation is common (Plate IV, D), and in one specimen a thin band of more siliceous rock is seen intensely contorted and disrupted. This specimen is cut by a network of sub-parallel shear-planes along which quartz and mica are ground down to a fine, nearly opaque dust, but the chloritoid is neither altered nor granulated.

Chloritoid laths in most specimens show a fairly strong preferred orientation parallel to the schistosity. In many examples, however, a proportion of the crystals—though evidently of the same generation—are haphazardly arranged. Where the rock is crumpled, the chloritoid laths follow the outlines of the contortion, and can be seen to curve round the apices of remarkably sharp folds (Plate IV, C and D). The mineral shows no signs of mechanical disruption, and it would seem that continuous crystal growth took place during the movements.

A series of specimens from the Scotia group on Scotiafjellet illustrates particularly well the progressive development of chloritoid in the vicinity of a zone of intense movement. As already mentioned, a number of subsidiary slides have here developed within the Scotia group above its junction with an underlying structural unit. Where not affected by thrusting, the rocks are low-grade slates. A specimen taken from a point 18 feet below the lowest of the minor thrusts is a fine-grained rock composed principally of quartz and sericitic mica ; small lenticular quartz segregations (less than 0·5 mm.) are common. Minute laths of chloritoid have developed haphazardly in the groundmass and, more conspicuously, in some of the quartz segregations. Many of them are almost at right angles to the schistosity. Six feet below the thrust the rock takes on a more fully recrystallized appearance. The quartz-chloritoid patches are larger and more numerous and tend to make the micaceous laminae less continuous. The proportion of chloritoid is higher and the laths are larger, though still stubby in shape. Less than 3 feet below the thrust, chloritoid develops on a still larger scale (Plate IV, B). Patches and lenses of quartz and chloritoid, up to 1 mm. across, are enveloped in thick micaceous folia. Within the micaceous layers the mica flakes lie parallel to the general foliation which sweeps around the quartzose lenses. Chloritoid occurring in these layers is lath-shaped and generally lies more or less parallel to the schistosity. The mineral occurs more abundantly in the quartz-rich areas where it forms rosettes and long needles arranged without regard to the schistosity. A specimen collected from 3 feet above the thrust is similar to that just described, but it has been modi-

fied by late shearing, with the formation of some retrogressive chlorite. The chloritoid, however, is unchanged. Twelve feet above the thrust the rocks are once more slates, dotted with tiny chloritoid laths.

Intense distortion of the rocks is exhibited along a higher thrust at the same locality. A quartzose band shows fantastic strain effects, the crystals being greatly elongated and showing strongly developed Bohm lamellae. Patches of mica are crumpled until under crossed nicols they have the appearance of shot silk. Abundant rosettes and needles of chloritoid have developed in pelitic bands alongside the deformed quartzose layer. They show no sign of alteration or granulation.

The chloritoid-bearing rocks of the *Kerr group* are essentially similar to those of the Barents and Scotia groups described above, though they are sometimes rather coarser in texture.

Discussion

Three points arise from a consideration of the field and microscopic data described above. In the first place, as already stated, chloritoid is confined to rocks of a single lithological type. It occurs only in grey or green pelitic rocks which are not very rich in quartz. The effect of this composition control is to limit the mineral to three of the stratigraphical groups. Rocks of appropriate composition make up a fairly large part of the Barents group. They occur only in one part of the Scotia group and it is noticeable that although both grey slates and black slates enter the zones of thrusting on Scotiafjellet, it is only in the grey slates that chloritoid develops. The other stratigraphical groups of Prince Charles Foreland, apart from the Kerr group, do not contain rocks lithologically comparable to those in which chloritoid occurs. Argillaceous types in these groups are generally either black or rather calcareous or somewhat silty. In none of these varieties has chloritoid been found.

Secondly, chloritoid occurs only in rocks which the field evidence shows to lie close to planes of intense movement. Many of these planes are definite thrusts involving very considerable displacements. The microscopic evidence in most cases confirms that the chloritoid-bearing rocks are very strongly deformed, and indicates that the growth of chloritoid was contemporary with the deformation. The mineral shows no strain effects comparable to those displayed by the quartz and micas of the ground-mass, but it sometimes forms curved crystals bending around the folded lamination of the rocks.

Finally, chloritoid develops in complete discordance with the pattern of regional metamorphism. The mineral occurs at widely scattered localities of which several are south of Scotiadalen, three are in a low structural unit (Unit 4) north of Scotiadalen, and three are in a higher

unit (Unit 3). South of Scotiadalen the rocks are uniformly in the biotite-grade of regional metamorphism. In Unit 4, to the north, chlorite-grade metamorphism prevails around Scotiafjellet, but further north near Rudmosefjellet, the rocks are in the biotite-grade. The whole of Unit 3 is in the chlorite-grade of regional metamorphism.

Chloritoid may thus be said to occur in any of these metamorphic settings where there is a coincidence of certain critical conditions of rock composition and structural situation. These two factors, which can be observed particularly clearly in Prince Charles Foreland, have in the past been held by many authors to be responsible for the distribution of chloritoid.

The restriction of chloritoid to rocks of a rather narrow range of composition has been noted by many geologists, for example, Niggli (1912), Tilley (1928), Cloos and Hietenan (1941). All these authors are agreed that richness in Al_2O_3 and Fe_2O_3, and poverty in CaO, alkalies and MgO, are characteristic of chloritoid-bearing rocks, and although no chemical analyses have been made of the chloritoid-bearing rocks of Prince Charles Foreland, they appear to be of the same general type as those occurring elsewhere.

The effect of movement or stress on the development of chloritoid has been discussed by numerous geologists, among them Niggli (1912), and Harker (1932) who referred to chloritoid among the " stress minerals", the minerals whose field of stability is enlarged by the application of stress. Other field examples suggesting that movement plays a part in facilitating the growth of chloritoid have been described by Cloos and Hieteman (1941) who found that in the Wickahisson Schists of Pennsylvania " it appears that rocks of the same bulk composition may contain chloritoid where they are strongly sheared but only chlorite where the stress has been weaker " (p. 119). Read (1937) showed that in Unst chloritoid developed in pelitic gneisses as a result of metamorphism associated with such phenomena as the granulation of quartz, bending of micas and the development of chlorite-filled shear-planes. Read (1951) attributed the production of chloritoid in the chloritoid slates of the Rand to the special stress environment provided by shales compressed between stiff competent bands, but considered that the occurrence of chloritoid in andalusite-chloritoid-hornfelses in the contact aureole of the Bushveld sheet indicates that the mineral can also appear under conditions of no stress. Seki (1954) likewise suggested that chloritoid can form under non-stress conditions, and has recorded in evidence the existence of chloritoid-bearing segregation veins (pp. 254–5). Michot (1955) describes chloritoid formed hydrothermally at the contacts of quartz veins " dans un mileu statique " (p. 39). Seki suggested that the importance of movement may lie in its effect in promoting chemical migration by means of

which a chemical environment suitable for the growth of chloritoid may develop. The reader is referred to his paper for a full bibliography on chloritoid-bearing rocks.

In Prince Charles Foreland there seems no doubt that a very close connection exists between the incidence of intense movements and the development of chloritoid, for the mineral is in many cases limited to a zone only a few tens of feet wide which is demonstrably a zone of dislocation. Although the exact part played by the movements remains, as in other localities, somewhat obscure, the field evidence seems sufficiently clear to be worth recording.

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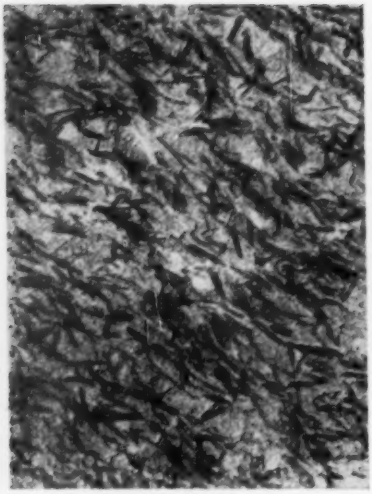

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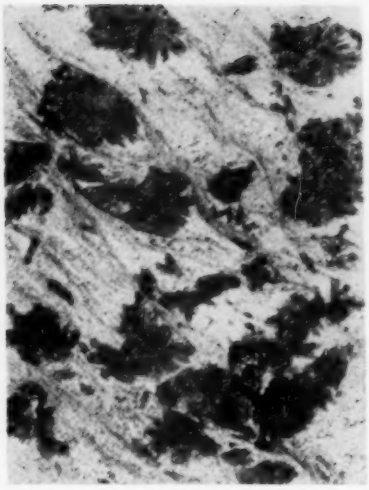

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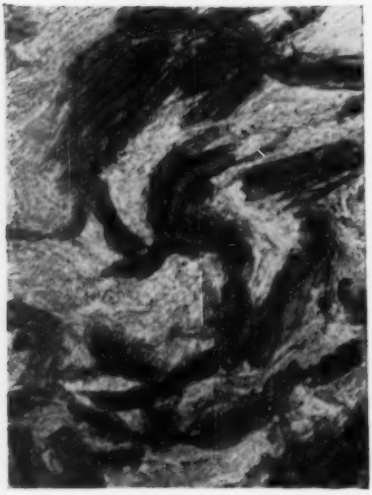

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EXPLANATION OF PLATE IV

A. Fine-grained quartz-sericite schist with small chloritoid laths. Murraybreen. × 35.

B. Micaceous schists with well-developed quartz-chloritoid lenses. Scotiafjellet. × 35.

C. Chloritoid-bearing schist showing curved chloritoid crystals. Murraybreen. × 70.

D. Chloritoid crystals curving round small folds in crumpled micaceous schist. Murraybreen. × 70.

The Mourne Mountains Granites—A Further Study

By P. E. Brown

Abstract

Chemical analyses and petrographic data are given of the eastern granites of the Mourne Mountains. It is shown that the main bulk of the granite is a uniform highly siliceous biotite-bearing type and that the intrusion of this was preceded by a smaller amount of less siliceous and more variable hornblende-bearing granite. The ferromagnesian minerals have a high iron to magnesium ratio.

Introduction

THE Mourne Mountains are the site of a Tertiary granite complex emplaced in Silurian shales. The structural relations of the granites were described by Richey (1928) who mapped four distinct intrusions composed of different varieties of granite, three of which occur in the east and the fourth in the west of the complex. Two of the eastern granites are in contact with the western granite along a length of about two miles and in plan the massif is of hour-glass shape. This paper is concerned with the granites in the eastern Mournes which Richey showed were emplaced by cauldron subsidence. These granites are distinguished as G1, G2, and G3 in order of emplacement and are arranged one within the other with marked eccentricity towards the south-east. The contacts between the granite are fine grained and the relationships between the individual roofs and walls of the three masses are remarkably similar. In each a slightly domed roof turns abruptly into a wall which is either vertical or inclined slightly outwards. G1 is bounded on the eastern side of the Mournes by a narrow screen of country rock which separates it from G1′, the later being dyke like in form and probably intruded into a ring fracture. In the present paper new petrographic, chemical, and mineralogical data is given for the eastern granites.

The Granites

It has been found that G1 varies both in texture and composition but that both G2 and G3 are essentially uniform masses.

1. *Granite G1.*

On the northern range of hills Slieve Donard, Slieve Commedagh, and Slieve Corragh, G1 forms a capping to G2 and the contact here is approximately horizontal. The rock is medium to coarse grained with phenocrysts of potash feldspar of the order of 2 cm. long. Potash feldspar and plagioclase (An_{12}) occur in the groundmass and the former has a poorly developed microperthitic texture. Both green hornblende

and intensely pleochroic biotite are present and vary in relative proportions, hornblende being best developed in the rock on Eagle Crag on Slieve Donard, where it occurs as ragged grains and less frequently as clusters of small interlocking crystals. The ferromagnesian minerals are always associated with iron ore. Two chemical analyses of the G1

TABLE 1

Granites G1 and G1′

	1	2	3	4	5	6
SiO_2	68·15	70·85	76·35	76·80	74·66	76·45
TiO_2	0·20	0·31	n.d.	0·08	0·15	0·04
Al_2O_3	15·95	13·58	13·65	13·04	13·12	13·53
Fe_2O_3	0·74	1·55	0·77	0·51	1·23	0·14
FeO	3·24	2·43	0·48	0·41	0·62	0·94
MnO	Tr.	Tr.	Tr.	Tr.	0·01	Tr.
MgO	0·04	0·01	0·02	Tr.	Tr.	Tr.
CaO	1·88	1·48	0·42	0·95	0·80	0·53
Na_2O	3·40	3·89	3·77	2·79	3·24	4·12
K_2O	5·00	5·37	4·78	4·98	5·59	4·27
H_2O+	0·22	0·55	0·21	0·23	0·51	0·14
H_2O-	0·65	0·16	0·08	0·04		0·02
P_2O_5	0·12	0·07	Tr.	0·02	0·06	0·02
Total	99·62	100·25	100·53	99·85	99·99	100·20

Norms

	1	2	3	4	5	6
Q	22·98	24·12	35·10	39·36	32·64	34·32
C	1·53	—	1·53	1·22	0·20	1·12
Or	29·47	31·69	28·36	29·47	33·36	25·58
Ab	28·82	33·01	31·96	23·58	27·25	34·58
An	9·45	3·61	1·95	4·73	3·89	2·50
Di	—	3·48	—	—	—	—
Hy	4·87	0·66	0·26	0·26	—	1·58
Mt	0·93	2·32	1·16	0·70	1·62	0·15
Il	0·46	0·61	—	0·15	0·15	—
Ap	0·34	—	—	—	—	—

1. G1. Eagle Rock, Slieve Donard. Richey, 1928. Analyst: W. Herdsman.
2. G1. Slieve Corragh. Analyst: P. E. Brown.
3. Contact of G1 to shale screen in Bloody River. Analyst: P. E. Brown.
4. Vein in shale screen, Bloody River. Analyst: P. E. Brown.
5. G1′. Ballagh River. Analyst: P. E. Brown.
6. Aplite in G1, Bloody River. Analyst: P. E. Brown.

" roof " rock (Table 1, analyses 1 and 2) show that the content of MgO is unusually low, a characteristic also shown in G2 and G3.

The main mass of G1 occurs on the eastern border of the mountains and is bounded, where exposed, by vertical contacts against G2 and against the narrow screen of shale which separates it from G1′. Good sections of this mass are exposed in the Bloody and Ballagh Rivers south of Newcastle, Co. Down. The average rock is medium-grained and granitic in texture, lacking the large feldpsar phenocrysts

found in the roof area of G1. Biotite forms some 3 per cent by volume of the rock but hornblende is very rare or absent. In hand specimen quartz is notably more abundant than in the hornblende-bearing areas already described. The feldspars are microperthite and plagioclase (An_{10}), the coarseness of the intergrowth in the former varying from grain to grain within a single thin section. It can be seen in the Bloody River section that the granite in contact with the screen of country rock is fine grained and passes to a slightly coarser variety some feet upstream. Though this contact is sharp and there is no merging of the granite and the shale, there is a little brecciation and several veins of very fine-grained granite penetrate the screen. Thin sections of the contact granite show that the grain size is variable. Granular

TABLE 2

Specimen No.	233	226	211	213	216	222	258
Distance from Contact.	Vein	Contact	3 in.	1 ft.	2 ft.	5 yd.	Approx. 550 yds.
K_2O	4·98*	4·78*	5·41	5·17	5·30	4·82	4·97
Na_2O	2·79*	3·77*	3·57	3·53	3·53	3·53	3·61
REPEAT DETERMINATIONS							
K_2O		4·66		5·28		4·77	
Na_2O		3·77		3·59		3·53	

* = gravimetric determinations, otherwise flame photometer method. Analyst: P. E. Brown.

areas of quartz and feldspar surround and sometimes penetrate larger crystals of the same minerals. Granophyric intergrowths are also present. The larger crystals of potash feldspar show a weak development of microperthitic texture but in the veins which penetrate the screen from the main body of granite this mineral is sometimes microscopically homogeneous. Two chemical analyses have been made of the Bloody River G1 granite, one of the contact with the shale screen and one of a granite vein penetrating the screen (Table 1, analyses 3 and 4). Comparison of these two analyses with those from the roof of the mass shows the extent of variation to be found within G1. A number of determinations of alkali content on specimens from the Bloody River section (Table 2) have shown a variation which may be due to (i) the heterogeneous texture of the chilled rock close to the contact, (ii) volatile action in the late stages of consolidation (see also section on granite G2).

Granite G1′ is well exposed in the Bloody and Ballagh Rivers where on one side it can be seen in contact with the country rock and on the other with the screen separating it from G1. Well rounded crystals of quartz and feldspar are set in a groundmass of the same minerals which may be granular or in micrographic intergrowth. Hornblende, intensely pleochroic from pale yellow to almost opaque green, occurs in extremely ragged clusters and as small grains scattered throughout the groundmass. A specimen of this rock collected close to the contact against country rock in the Ballagh River (Table 1, analysis 5) is essentially similar to the Bloody River G1 but contains slightly less silica.

2. *Granite G2.*

In its typical development this granite is medium to coarse grained with very abundant quartz, a large proportion of which is unusually dark in colour, this being one of the diagnostic features of the intrusion (Richey, 1928). In general the feldspar is not porphyritic though in some localities it is slightly so. The margin of G2 against G1 and against the country rock is chilled. The whole G2 intrusion has a conspicuous mariolitic texture and many hand specimens have a profusion of small cavities some millimetres in diameter, the maximum development being on the " Diamond Rocks " to the west of Slieve Donard where the druses often measure inches across and occasionally contain rare accessory minerals. This mariolitic texture indicates that the rock was rich in volatiles at the time of emplacement. The most abundant mineral in G2 is potash feldspar which within a single thin section shows all gradations of microperthitic structure from fine uniformally parallel exsolution lamellae, through anastomizing veins to patchy segregations showing multiple twinning. Though unmixing of an originally single phase mineral will explain the present texture of the perthites it is possible that the development of the coarser types of perthite has been assisted by volatile action in the late stages of consolidation. Such action may account for any alkali variation that is found within the granites. The feldspar is usually cloudy due to sericitization. Biotite occurs throughout G2 as ragged grains and clusters of such grains; it frequently has green chloritic edges and is associated with iron ore and zircon. Four chemical analyses of G2 are now available. These show a high degree of uniformity and confirm the opinion formed from hand specimens and thin sections that G2 is essentially uniform in composition. The distribution of alkalies appears to be uniform except that the contact specimen from Slieve Donard shows an increased soda to potash ratio. The silica content of G2 is greater than that of any other Tertiary granite from the British province, the north Arran granite (Table 3, analysis A) being the most

TABLE 3

Granites G2 and G3

	1	2	3	4	A	5	6	7	8
SiO_2	77·51	77·27	76·95	77·06	74·87	77·52	75·24		
TiO_2	0·09	0·13	0·12	0·13	0·26	0·07	0·07		
Al_2O_3	12·03	12·49	12·57	11·90	11·24	12·10	13·25		
Fe_2O_3	0·04	0·34	0·35	0·27	0·34	0·38	0·44		
FeO	1·20	1·08	0·96	1·17	1·22	0·66	0·86		
MnO	0·03	0·02	Tr.	0·02	0·05	0·02	0·02		
MgO	Tr.	Tr.	Tr.	0·16	0·22	0·21	Tr.		
CaO	0·71	0·66	0·61	0·71	1·30	0·51	0·67		
Na_2O	3·32	3·11	3·87	3·44	3·31	3·36	4·13	3·26	3·15
K_2O	4·84	4·71	4·52	4·94	5·68	4·78	5·13	4·65	4·64
H_2O+	0·25	0·23	0·37	0·38	0·49	0·28	0·15		
H_2O-	0·02	0·07	0·09	0·07	0·29	0·15	0·23		
P_2O_5	Tr.	Tr.	0·03	0·01	0·09	0·01	0·11		
F	0·17	—	—	—	—	—	—		
BaO	Nil	—	—	0·03	0·04	0·02	—		
Rest	—	—	—	0·07	0·84	0·14	0·14		
Total (less O for F)	100·15	100·11	100·44	100·36	100·24	100·17	100·44		

Norms

	1	2	3	4	5	6
Q	37·56	39·00	35·10	36·06	37·62	30·78
C	0·31	1·02	0·20	—	0·41	0·41
Or	28·36	27·80	26·69	28·91	28·36	30·02
Ab	27·77	26·20	33·01	28·82	28·82	34·58
An	3·06	3·61	3·06	2·78	2·50	1·67
Di	—	—	—	0·71	—	—
Hy	2·11	1·58	1·32	1·88	1·29	1·19
Il	0·16	0·15	0·15	0·15	0·15	0·15
Mt	—	0·46	0·70	0·46	0·70	0·70
Fl	0·39	—	—	—	—	—
Ap	—	—	—	—	—	0·26

1. G2. Granite quarries, Newcastle. Analyst: H. F. Harwood. (Nockolds and Richey, 1939.)
2. G2. Head of Bloody River. Analyst: P. E. Brown.
3. G2. Fine grained contact to G1, Eagle Rock, Slieve Donard. Analyst: P. E. Brown.
4. G2. Annalong end of water works tunnel, 907 yards from entrance (*Geol. Surv. Summ. Prog.*, 1953). Total includes S 0·02, Li_2O 0·01, Rb_2O 0·04. Analysts: A. D. Wilson and P. Combs.

A. Northern Arran granite (*Mem. Geol. Surv.*, 1928). Total includes Cr_2O_3 0·02, FeS_2 0·33, CO_2 0·49. Analyst: B. E. Dixon.

5. G3. Mourne Mountain tunnel, Silent Valley end (*Geol. Surv. Summ. Prog.*, 1953). Total includes S 0·03, Li_2O 0·02, Rb_2O 0·05. Analysts: A. D. Wilson and P. Combs.
6. G3. Quarry west end of dam in Silent Valley. Analyst: E. M. Patterson (1953).
7. Contact of G3 to G2, Ben Crom, Silent Valley. Analyst: P. E. Brown.
8. G3. Slievenaglagh. Analyst: P. E. Brown.

comparable. G2 is unusual in containing only a trace amount of MgO and the amount of this oxide in the north Arran granite is more typical of high silica granites in general. Analysis 4 (Table 3) is the only one of G2 showing a significant amount of MgO and if the specimen analysed was typical G2 granite it is difficult to account for the figure given. Biotite is the only mineral which could contain appreciable amounts of magnesia. This mineral forms only 2 or 3 per cent of the rock by volume and is evenly distributed throughout the intrusion. The analysis of biotite from the Newcastle G2 granite quarries (Table 5)

TABLE 4

Modal Analyses

	1	2	3	4	5	6
Perthite . . .	55	54	39	38	44	36
Quartz . . .	23	26	40	38	36	36
Plagioclase . .	13	14	19	21	17	25
Hornblende . .	8	5	—	—	—	—
Biotite . . .	—	1	2	3	3	3
Accessories (mainly Iron Ore).	1	—	—	—	—	—

1. Hornblende variety of G1, Eagle Crag, Slieve Donard.
2. G1. East side of Slieve Donard.
3. G1. Bloody River section.
4. G2. Average rock.
5. G3. Average rock.
6. Aplite in G1, Bloody River.

shows that the mineral does not contain sufficient MgO to account for the figure given in analysis 4.

3. *Granite G3.*

This intrusion is fine grained for a considerable distance from its contact against G2 and in places the fine grained margin is several hundred yards in width before grading into coarser granite which is essentially similar, both in hand specimen and thin section, to G2. The whole mass of G3 is mariolitic and some specimens have a profusion of small cavities several millimetres in width lined with euhedral crystals of quartz and feldspar. The rock is not porphyritic and the fine grained margins have a granular texture which led Richey to refer to this intrusion as the " aplitic granite ". These fine grained margins are characterized by granophyric intergrowth of quartz and feldspar which persists to a lesser degree in the centre of the mass. Biotite occurs throughout G3. Two chemical analyses are available of G3 (Table 3, analyses 5 and 6). Analysis No. 5 shows 0·21 per cent MgO and as the volume of dark minerals in G3 is not significantly greater

than in G2 it is considered that the determined value of magnesia is too high. The chemical data confirms the similarity of G2 and G3.

4. *The Aplites.*

Aplites are conspicuous in all the granites occurring as dykes usually between 6 inches and 2 feet in width. They bear a distinct chemical and mineralogical resemblance to the type of granite in which they occur, the main difference being their smaller grain size and

TABLE 5

	wt. %	1 Metal Atoms (24 O, OH)			A	B	C
SiO_2	38·77	6·242	8·00		39·56	38·24	37·88
Al_2O_3	10·08	1·758			12·18	10·17	10·57
		0·152					
TiO_2	2·56	0·309			1·46	2·00	3·53
Fe_2O_3	4·07	0·491	5·211		4·10	5·00	4·42
FeO	26·54	3·570			23·18	26·64	26·08
MnO	0·60	0·082			0·09	0·28	0·60
MgO	2·53	0·607			4·43	1·07	1·95
CaO	9·65	1·663			9·98	10·64	8·97
Na_2O	1·61	0·502	2·408		1·81	1·50	2·02
K_2O	1·18	0·243			1·38	1·57	1·52
H_2O+	1·85	1·987	1·987		1·26	1·88	1·30
H_2O-	0·06				—	0·08	0·54
F	n.d.				1·20	1·06	—
Total	99·50			Total (less O for F)	100·12	100·07	99·52
α	1·696			α	1·690	1·702	—
β	—			β	1·702		—
γ	1·710			γ	1·711	1·730	—
2V	52°			2V	55°	0°	—
α	Yellow green						
β	Olive green						
γ	Dark green						
Sp. gr.	3·41						

1. G1. Hornblende, Eagle Crag, Slieve Donard. Analyst: P. E. Brown.
A. Hornblende from Rubideaux Mountain granite, Batholith of Southern California (Larsen and Draisin, 1948).
B. Amphibole from Rapakivi granite, Uuksonjoki, Finland (Sahama, 1947).
C. Amphibole from Senzan granite, Manchuria (Yosizawa, 1941).

granular texture. One of the aplites in the Bloody River G1 has been analysed (Table 1, analysis 6), and its composition should be compared with that of the other granites and particularly with the margin of G1 in the Bloody River which it closely resembles. It is evident that the aplites, unlike most rocks of this type, do not differ significantly in composition from the granite in which they are found and probably

represent late stage injections of the same magma into the partially solidified mass.

5. *The Ferromagnesian Minerals.*

Ferromagnesian minerals from rocks as siliceous as the Mourne granites have so seldom been analysed that it was considered appropriate to separate the hornblende from G1 and biotite from G2. The separation of both minerals was effected by the use of an electromagnetic separator and centrifuging in heavy liquids. Samples of both

TABLE 6

	1			A	B
	wt.%	*Metal Atoms 12(O, OH)*			
SiO_2	35·40	2·870	4·00	35·96	37·17
Al_2O_3	11·82	1·130		14·36	14·60
TiO_2	2·14	0·131	2·57	5·32	3·14
Fe_2O_3	9·52	0·581		1·42	3·75
FeO	25·09	1·701		26·16	26·85
MnO	0·67	0·046		0·04	0·06
MgO	0·95	0·115		5·59	4·23
CaO	Tr.	—		0·54	0·17
Na_2O	1·54	0·242	1·17	0·53	0·15
K_2O	9·02	0·932		8·62	8·25
H_2O+	3·64	1·968	1·97	1·10	1·35
H_2O-	Nil			—	—
F	n.d.			0·21	0·85
Total (less O for F).	99·86			99·76	100·21
α	—			1·602	1·610
β	1·653			1·670	1·676
γ	1·653			1·673	1·677
2V	0°			12°	5°
α	Pale yellow brown				
$\beta = \gamma$	Dark brown				

1. G2. Biotite, quarries, Newcastle. Analyst: P. E. Brown.
A and B. Biotites from Rubideaux Mountain granite, batholith of Southern California (Larsen and Draisin, 1948).

minerals were obtained with over 99·5 per cent purity. The outstanding characteristic of their composition is the high FeO to MgO ratio.

Hornblende.

Details of this mineral are given in Table 5. The somewhat low total of the analysis may be due to non-determination of fluorine. Low SiO_2, a CaO content of 9·65 per cent, and the high FeO to MgO ratio show the mineral to be hastingsite. Analysis A, Table 5, is of hornblende from the Rubideaux Mountain granite, batholith of Southern California (Larsen and Draisin, 1948); this analysis compares

very closely with that of the Mourne amphibole. Similar composition and optical properties are shown by amphiboles from Rapakivi granite in Finland (Sahama, 1947), and from the Senzan Granite, Manchuria (Yosizawa, 1941), Table 5, analyses B and C. All these analyses are remarkably similar and indicate that this type of amphibole is typical of highly siliceous granitic rocks in general.

Biotite.

The composition and structural formula of the G2 biotite are given in Table 6, and compared with analyses of two biotites from the Southern California batholith. The Mourne biotite shows an even greater iron to magnesia ratio than the hornblende and contains only a trace amount of calcium. Larsen and Draisin (1948) found a progressive decrease in alumina in biotites from the more siliceous rocks of the Southern California batholith and it is interesting to note that the Mourne biotite contains just sufficient alumina to make up the deficiency of silica in the silicon-oxygen tetrahedra.

6. *The Feldspars.*

The 2V of the potash feldspars in the Mourne granites varies considerably from grain to grain within a single thin section, but in the contact of G1 to the shale screen in the Bloody River the values of 2V are unusually low for this mineral in granites. Measurements of 2V have been made at increasing distances from the contact (Table 7) by the method of direct determination in thin section on the universal stage, the value quoted being the average of eight or ten readings on each individual crystal (Fairbairn and Podolsky, 1951). The values are in general reproducible to $\pm 1°$. The potash feldspars of the granite veins penetrating the screen are generally optically homogeneous. In the contact rock similar potash feldspars are present though there are grains with a weak microperthitic texture. Within a foot of the contact the microperthitic texture is fairly well developed becoming more so further from the contact. The 2V of potash feldspars is dependent on the plagioclase content and on the degree of inversion to cryptoperthite or perthite (Tuttle, 1952). The significance of the variation of 2V in the Mourne feldspars can only be deduced by determining the composition and degree of unmixing on individual crystals. This has been done by Drs. Mackenzie and Smith for crystals in two specimens from the Bloody River G1, one of the coarse average granite and one of the fine grained contact rock (actually an off-shoot of the granite 3 inches within the shale screen). On three crystals of potash feldspar from the coarse granite the optic axial angles were 66°, 59°, and 58°, and the mineral consists of unmixed potash and low albite phases; no attempt was made to homogenize the mineral

but from the relative intensity of the reflections from the soda and potash components the composition was estimated at $Or_{70}Ab_{30}$. In the fine grained specimen optic axial angles were obtained between 42° and 47°. Two crystals were X-rayed and found to consist of a single potash phase with a small amount of the soda phase; there is little unmixing and the composition was determined as $Or_{85}Ab_{15}$. The values of 2V and the composition indicate that the mineral is a

TABLE 7

Distance from Contact.	*Optic axial angle of potash feldspars, individual grains.*				
Granite vein in screen	41	42	39	37	44
	44	38	43	41	39
	46	46	39	45	39
	47				
Ditto . . .	35	33	40	39	
	37				
Contact of granite to shale screen.	48	51	50	54	
	49	51			
1 ft. . . .	56				
1½ ft. . . .	52	53			
2 ft. . . .	50	53			
390 ft. . . .	53				
1,500 ft. . .	56	63			
3,600 ft. . .	69	64	61		

member of the low albite-orthoclase series (Tuttle, 1952). There is evidently a wide range in composition of the potash feldspars in G1.

DISCUSSION

Support for the view that the Mourne granites were emplaced in a liquid or largely liquid condition is afforded by the following evidence:—

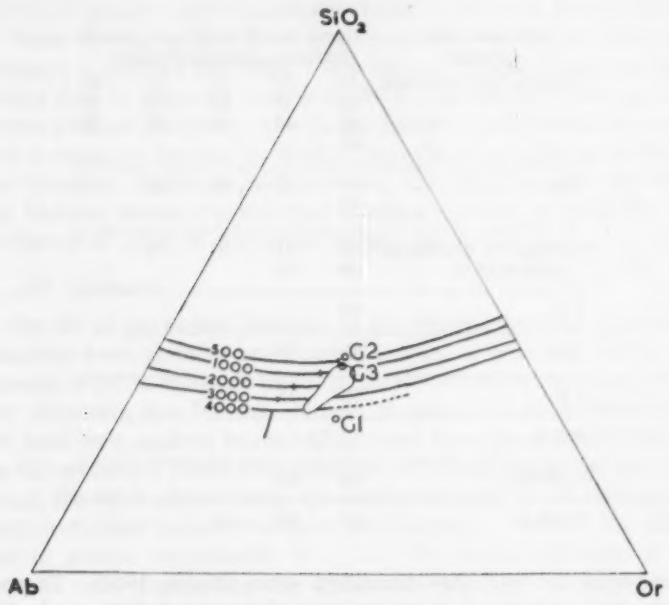
(*a*) Intrusion by cauldron subsidence; each of the granites G1, G2, and G3 have well developed chilled margins against older rock and granophyric intergrowth is usually present in these margins.

(*b*) The drusy nature of the granites indicates a semi-liquid condition at the time the cavities developed.

(*c*) The overall uniform texture of G2 and G3 is characteristic of magmatic granites in general (Goodspeed, 1948).

(*d*) The presence of cross-cutting aplite dykes with the same composition as the parent granite.

If a magmatic origin is accepted the origin of the magma must be sought in refusion or in differentiation from more basic material. It has been shown (Bowen, 1954) that the naturally occurring granites show a close correspondence to the minimum temperature trough (for various pressures of water vapour) in the system albite, orthoclase, quartz. These results support the view that many granites originated by crystallization of the liquid residuum of fractional crystallization



TEXT-FIG. 1.—Equilibrium crystallization diagram for mixtures of albite, orthoclase, and quartz showing position of boundary curve between the fields of quartz and feldspar at various pressures of water vapour indicated in atmospheres on each curve. The crossbar on each curve indicates the position of minimum temperature for that curve. The position of granites G1, G2, and G3 are indicated. The closed contour represents the area of densest distribution of naturally occurring granites and syenites. (Diagram after Bowen, 1954.)

or by crystallization from the liquid produced by selective refusion of pre-existing rocks. The Mourne granites G2 and G3 plot close to the minimum point for low pressures of water vapour in the system Or–Ab–Qtz (Text-fig. 1), while the more basic G1 does not show any simple relation to the trend of minimum temperature in the system.

Cook and Murphy (1952) have shown that there is a large positive gravity anomaly in the Slieve Gullion–Carlingford–Mourne Mountain

area. These authors concluded that the anomaly was due to two large bodies of basic igneous rock, one beneath the Slieve Gullion and Carlingford area and the second on the southern border of the Mourne Mountains. Cook and Murphy suggest that though the surface outcrop of acid rock predominates, the total mass of basic rock underlying the region must be at least a hundred times greater. The detailed form of the underlying basic masses cannot be determined from the gravity data, nor can any precise idea of the depth of the bodies be obtained, but the thickness of the granite in the western Mournes was estimated at only 3,000 to 4,000 feet. It is possible that the basic mass indicated by the gravity anomaly was the magma from which the granite developed by differentiation, but it is equally possible that it might have been responsible for the refusion of pre-existing material thus leading to the development of granitic magma.

Confirmation of the view that the origin of the Mourne granites must be sought in refusion is found in the association of both acid and basic magmas in the pre-granite dyke swarm, described by Tomkeieff and Marshall (1935). These authors explained the simultaneous existence of the two magmas by application of the syntectic hypothesis of Holmes (1931 and 1932). The intrusion of the main body of granite was followed by further acid and basic dykes and the two magmas were available throughout the whole period of igneous activity. The origin of the hornblende variety of G1 with its wide variation of silica is considered to be the result of deep-seated hybridization of the granite by the basic magma in a manner analogous to the hybridization in the Glasdrumman composite dyke (Tomkeieff and Marshall, 1935).

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DEPARTMENT OF GEOLOGY,
UNIVERSITY, MANCHESTER.

CORRESPONDENCE

UPPER EUMORPHOCERAS BEDS ON BENBRACK, COUNTY CAVAN.

SIR,—*Eumorphoceras bisulcatum* Girty has been collected from the shales at the summit of Benbrack (1,648 ft.), the mountain south of Cuilcagh (2,188 ft.). These beds, of E_2 age, are therefore the youngest beds yet recorded in this large North Central Irish Millstone Grit outlier. Due to the comparatively flat block-faulted structure of the outlier the youngest beds occur on the hill-tops, but Padget (1953, p. 25) states that no diagnostic fossils of the E_2 stage were found on Cuilcagh, where his described succession ends well below the summit.

Dr. F. Hodson informs me that the highest beds on Dough Mountain and Black Mountain in the north-west of the outlier do not range into the E_2 stage. According to the Geological Survey of Ireland one-inch map (Sheet 56) higher beds than those on Benbrack outcrop to the south-west on Bencroy and might be expected eventually to yield goniatites of higher level, though it seems unlikely that any true Westphalian Coal Measures occur there as indicated on the Geological Survey map.

The specimen has been deposited in the Geological Survey Museum, London (No. 95317).

GEOLOGY DEPARTMENT,
IMPERIAL COLLEGE,
LONDON, S.W.7.
6th December, 1955.

PATRICIA J. YATES.

REFERENCE

PADGET, P., 1953. The Stratigraphy of Cuilcagh. *Geol. Mag.*, xc, 17–26.

NOTICE

ZOOLOGICAL NOMENCLATURE

Notice is hereby given that the possible use by the International Commission on Zoological Nomenclature of its Plenary Powers is involved in applications relating to the undermentioned names included in Part 9 of Volume 11 of the *Bulletin of Zoological Nomenclature*, published on 30th December, 1955.

(1) *Phillipsinella* Novák, 1886 (Class Trilobita), validation of (Z.N.(S.)757).

(2) SEGUENZICERATIDAE Spath (L.F.), 1924 (Class Cephalopoda, Order Ammonoidea), suppression of (Z.N.(S.)931).

Any specialist who may desire to comment on any of the foregoing applications is invited to do so in writing to the Secretary to the International Commission (Address : 28 Park Village East, Regent's Park, London, N.W. 1, England) as soon as possible. Every such comment should be clearly marked with the Commission's File Number as given in the present notice.

If received in sufficient time before the commencement of voting by the International Commission on the applications in question, comments received in response to the present notice will be published in the *Bulletin of Zoological Nomenclature* ; comments received too late for publication will be brought to the attention of the International Commission at the time when voting commences on the application in question.

REVIEWS

FOSSIL PLANTS OF THE CARBONIFEROUS ROCKS OF GREAT BRITAIN (Second Section). By ROBERT CROOKALL. Mem. Geol. Surv., Palaeontology, Vol. IV, Part I. London, H.M.S.O., 1955. Price £3.

This very well illustrated Memoir is a continuation of the series on this subject which was broken by Dr. Kidston's death thirty years ago. The genera described in this part are *Alethopteris*, *Lonchopteris*, *Caulopteris*, and *Megaphyton*, but many important forms such as the species of *Neuropteris* remain to be published. It is hoped that in order to make this work really useful, the Geological Survey will be able to print the remaining six proposed parts quickly.

Dr. Crookall's monographic treatment includes reproduction in the text of all the " original " type figures, accompanied by some of his very clear sketches of pinnule venation. The collotype plates of British specimens are excellent.

The systematic work is preceded by a five-page discussion on the use of plants in Coal Measure correlation. A table gives the frequency of occurrence of 110 plant (mostly fern-like) species in the four Westphalian divisions ; from this are drawn short lists of " significant " plant species for each division. Dr. Crookall in using Westphalian A–D as agreed at the Second Heerlen Congress, rejects the Dix system of zones which he does, however, list on a table relating to the South Wales Coalfield. Apart from the brevity of this discussion, the approaching completion of this major work is very welcome.

N. F. H.

STRATIGRAPHICAL PALAEONTOLOGY, A STUDY IN ANCIENT LIFE-PROVINCES. By E. NEAVERSON. xii + 806 pp., 90 figs., 18 pls. Second edition, revised and enlarged. Oxford University Press, 1955. Price £5 5*s*.

This much enlarged edition of a familiar text-book may be considered separately as a revision and under its new and ambitious alternative title.

The author has corrected minor faults and in some places whole paragraphs are re-written but the original text is preserved in full to a surprising extent. The chapter on " Morphology of fossils " which was criticized in the first edition, has disappeared, but some of its text and all of its figures are included in the new Chapter II, " Fossils as Guides to Horizon." All the figures of fossils have been preserved from the first edition and there are very few additions; the photographs (mostly of ammonites) are bunched inexplicably beyond the elaborate index which is in five separate divisions. Indications of scale are now provided with all illustrations. The text appears to have been revised until about 1940 or in a few cases a little earlier, there being virtually no reference to later work ; the usefully annotated lists of classical references are given as in the first edition, in a succession which makes their use very tedious unless the whole chapter is read. Dr. Neaverson takes a strangely firm line over the sub-division of the Ordovician where he goes back to original usages to eliminate the Llanvirn and to preserve the Bala intact; the Llandeilo thus becomes *murchisoni* to *gracilis* inclusive. He is apparently unable to prevent the offending innovations from creeping into his text and however worthy the scheme, it seems a little late in the day to introduce it to students without first fighting it out with the present Palaeozoic experts on a discussion basis. The author avoids throughout some of his special dislikes such as the terms " facies-fauna " and " geosyncline " and he deliberately uses the divisions Palaeo-, Meso- and Neo- for the Lower, Middle and Upper in each system. A good new feature is the insertion of three full chapters on Land Faunas of the world but unhappily these are segregrated from the plants they lived on, which languish in a single largely out-of-date chapter, the latest reference to Mesozoic plants being in 1925.

The additions to the book consist mostly of a section entitled " Faunal

Regions " added to the end of the chapter on each system. These sections are illustrated by some distribution maps of " critical areas ". The information given is full but the text here is crammed with detail given for the whole world by continents; often there is little comment or connection and again the references virtually cease (with minor exceptions) after 1940. Handling such diverse material is never easy and although there would clearly be difficulties it is suggested that tabulations of fact accompanied by short comment and more maps would be much easier to use; it might even give some lead toward synthesis. An interesting concluding chapter on " General Relations of the Continents and Oceans ", brings the author to vote for stable ocean basins with fluctuating margins, having disposed of the necessity of both land-bridges and continental drift on palaeontological grounds.

In general this large compilation contains much valuable information but it is likely to disappoint because, for reasons given above, it will be difficult to use; Dr. Neaverson has attempted something which can probably no longer be done by one man. While the author of such a work should select and reject references, the omission from many chapters of all recent works leaves the suspicion that they have not been considered rather than that they have been rejected.

N. F. H.

PUBLICATIONS RECEIVED

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C. C. Beringer. *Geschichte der Geologie und des Geologischen Weltbildes*. Ferdinand Enke Verlag, Stuttgart, 1954. pp. vii + 158. Price DM 11.70 (bound).

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1 Bd. *Allgemeine Geologie* pp. viii + 286, with 207 figs. 1956. Price DM. 28·00 (bound).
2 Bd. *Historische Geologie*. pp. vii + 359 with 70 figs. 1954. Price DM. 35·00 (bound).
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Abhandl. d. deutsch. Akad. der Wissenschaft zu Berlin, Jahrg. 1953, no. 3, Beitrage zur Tektonik des Thüringer Beckens, by S. VON BUBNOFF and others, 168 pp. with 5 pls.; 69 text-figs. and numerous maps and sections in folder, DDR Berlin, 1955, price 54M.

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Norsk Polarinstitutt Skrifter nr. 108. Late-Pleistocene Deposits at Kapp Wijk, Vestspitsbergen, by R. W. FEYLING-HANSSEN. 21 pp., with 3 pls. and 8 text-figs. Oslo, 1955.

Geological Survey of Taiwan. Geological map of Taiwan, colour printed, in 2 sheets, scale 1 : 300,000. 1953, no price.

CHELSEA POLYTECHNIC, S.W. 3

HEAD OF DEPARTMENT OF GEOLOGY

The Governors invite applications for the post of HEAD of the DEPARTMENT OF GEOLOGY which becomes vacant through the retirement of Dr. W. F. Fleet. Candidates should possess high qualifications in Geology, and have had experience in both teaching and research.

Salary Scale—Grade II (Men, £1,065—£25—£1,215; Women, £912 17s.—£1,215), plus London allowance of £36 or £48 according to age. Duties to commence 1st September, 1956. Further particulars and form of application may be obtained by sending stamped addressed foolscap envelope to the undersigned, to whom applications must be returned as soon as possible.—N. M. H. LIGHTFOOT, M.A., F.R.S.E., Principal.

THE GEOLOGICAL SOCIETY OF AMERICA

419 West 117 Street, New York 27, N.Y.

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